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MONTHLY WEATHER REVIEW

First published in 1872, the Monthly Weather Review serves as a medium of publication for technical contributions in the field of meteorology, principally in the branches of synoptic and applied meteorology. In addition each issue contains an article descriptive of the atmospheric circulation during the month over the Northern Hemisphere with particular reference to the effect on weather in the United States. A second article deals with some noteworthy feature of the month's weather. Illustrated. Annual subscription: Domestic, $3.50; Foreign, $4.50; 30 cents per copy. Subscription to the *Review* does not include the *Supplements* which have been issued irregularly and are for sale separately.

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(Continued on inside back cover)

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The issue for each month is published as promptly as monthly data can be assembled for preparation of the review of the weather of the month. In order to maintain the schedule with the Public Printer, no proofs will be sent to authors outside of Washington, D. C.

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THE USE OF PROBABILITY STATEMENTS IN EXTENDED FORECASTING

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ABSTRACT

The need for qualification of weather forecasts has long been recognized. The diverse uses of predictions and variations in the forecaster's ability to prognosticate weather events correctly have suggested to previous writers that expressions of confidence or other means of weighting can serve the public to advantage. A particular method of expressing and scoring 5-day temperature forecasts in terms of probability statements has been tried experimentally by the U. S. Weather Bureau's Extended Forecast Section and found to provide valuable information in addition to that normally furnished. Furthermore, it is demonstrated that the participants in the experiment possess definite skill in selecting probability statements, and that relative verification results are comparable to those obtained by scoring the conventional forecasts.

INTRODUCTION

Since weather forecasting is not an exact science, an individual prediction can at best be the forecaster's opinion of the weather events most likely to follow the antecedent conditions. Current practice in both short-range and extended forecasting involves the expression of this opinion in terms of categorical statements, the deficiencies of which have been discussed by investigators dating back at least to 1906 (Cooke [4]) and, more recently by Thompson [16]. It is the purpose of this paper to explore the need for a different form of expression, namely probability statements; to investigate the mechanics of expression for extended forecasts; and to determine the practicality of instituting a program of this type.

THE NEED FOR PROBABILITY INFORMATION

Although conventional forecasts are of obvious value to the public, they suffer from three major defects independent of their accuracy. In the first place, the forecast user is often interested in the likelihood of occurrence of a weather event which is not considered by the forecaster as "most likely" among the possible eventualities and hence, conceivably, is left unmentioned in the ordinary categorical forecast (Hallenbeck [9], Price [14]).

A second defect is inherent in the fact that the same categorical forecast may be issued by the same forecaster on two occasions of considerably different circumstances. This problem was recognized almost 50 years ago by Cooke [4] who stated: "It seems to me that the condition of confidence or otherwise forms a very important part of the prediction, and ought to find expression." This position was stated even more strongly in a report of a Special Committee on Forecast Verification, appointed by the Chief of the U. S. Weather Bureau in 1939, and quoted by Brier [1]: ". . . a mere forecast of an event without some qualification when the forecaster knows that there is considerable uncertainty would be withholding from the public information to which it is entitled." In the past, however, qualification has generally been expressed in the form of vague "weasel words". Only in the light of recent technical advances has it become possible to review the problem and evaluate the forecaster's capabilities along these lines.

The practical significance of furnishing all possible forecast information to the consumer derives from the fact that forecast value varies with the forecast user (Brier in "Panel Discussion on Forecast Verification" [13], and Brier and Allen [3]). Similarly, Thompson [16]

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concludes that issuing categorical weather predictions to individuals or agencies charged with making operating decisions ". . . in many cases places an appreciable handicap on the most effective use of the prediction."

The third shortcoming of categorical weather forecasts stems from the verification of predictions. In attempts to improve performance scores, forecasters often resort to "hedging" which, according to Brier [2], "may lead the forecaster to forecast something other than that which he thinks will occur, for it is often easier to analyze the effect of different possible forecasts on the verification score than it is to analyze the situation."

EXPRESSION AND USE OF CONFIDENCE STATEMENTS

Many investigators have advanced proposals to include or substitute statements of the probability of occurrence of the predicted weather events in order to circumvent one or more of the difficulties described above. Cooke [5], for example, suggested that a single figure be appended to each forecast to indicate the probability subjectively assigned by the forecaster. Thompson [16] also recommends that the consumer's problems of basing operational decisions can be relieved by " providing an estimate of the probability of occurrence of critical weather and permitting the user to make his own operating decision." This procedure is also supported by Brier and Allen [3] who advocate a scheme of probability forecasting and verification "that cannot influence the forecaster in any undesirable way. . . . (The) forecaster is encouraged to minimize [i. e., in their context, optimize] his score by getting the forecasts exactly right and stating a probability of unity. If he cannot forecast perfectly, he is encouraged to state unbiased estimates of the probability of each possible event. . . . The user can then interpret the information in terms of his operation."

An ideal scheme of expression of forecasts has been aptly described by Gringorten [7]: "if the forecaster could state the percent likelihood of each of all possible mutually exclusive events, he would be giving a complete answer as to his evaluation of the weather prospects." Of course, it is immediately self-evident that the crux of the matter lies in the forecaster's ability to analyze the situation and correctly assess likelihood of occurrence. Although a question has also been raised as to the ability of the general public to comprehend probability statements, it is usually recognized that most laymen readily understand the "odds" quoted for sporting events. Of even greater importance, however, is the fact that a complete statement of the probabilities of occurrence of all possible weather events automatically includes an indication of what the forecaster considers to be the most likely, that is to say, the conventional categorical forecast. Furthermore, with reference to the experiment to be described below, the 5-day temperature forecasts prepared by the Extended Forecast Section are not transmitted to the general public directly, but rather to District Forecast

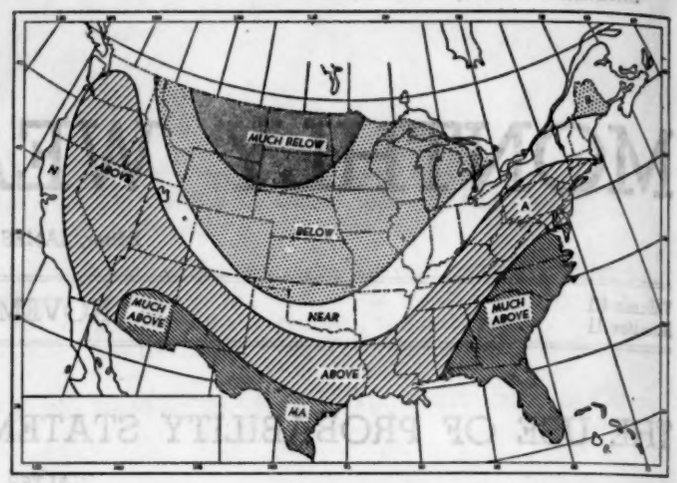

FIGURE 1.—Five-day temperature forecast (schematic) in terms of anomaly categories.

Centers where the recipients are well equipped to interpret probability statements.

From the forecaster's standpoint, it is also worth mentioning that the use of complete forecast information—including estimates of events not expected to occur—provides a better measure of his predictive ability if we agree with a definition of skill advanced by Gringorten [8]: "the forecaster's ability to analyze and classify the antecedent weather so that, within one class, the probability of a subsequent event is increased above, or decreased below, the relative frequency of that event in all weather situations (. . . the 'climatic frequency')."

EVALUATION OF PROBABILITY

The methods proposed for stating confidence in a categorical forecast or complete probability information over the full range of possible occurrences have varied from entirely subjective assessments, as discussed by Cooke [5] and Williams [17], to wholly objective techniques, as recommended by Dickey [6], Gringorten [7], and Thompson [15]. These writers, however, have concerned themselves almost exclusively with the problem of expressing the forecast for a single meteorological variable at a single locale, although extending the scope of the predictions increases only the procedural difficulties and not the basic principles involved.

At the Weather Bureau's Extended Forecast Section, circulation, temperature, and precipitation prognoses are prepared twice weekly and transmitted to regional meteorological centers where they may be modified on the basis of latest developments and knowledge of local characteristics before dissemination to the public. The temperature predictions, with which we are concerned in this paper, are made in terms of five categories of departure from normal: *near* normal, *above* and *below* normal, *much above* and *much below* normal (Namias [11, 12]). These categories are defined on the basis of records at individual stations for each month of the year in such a way that

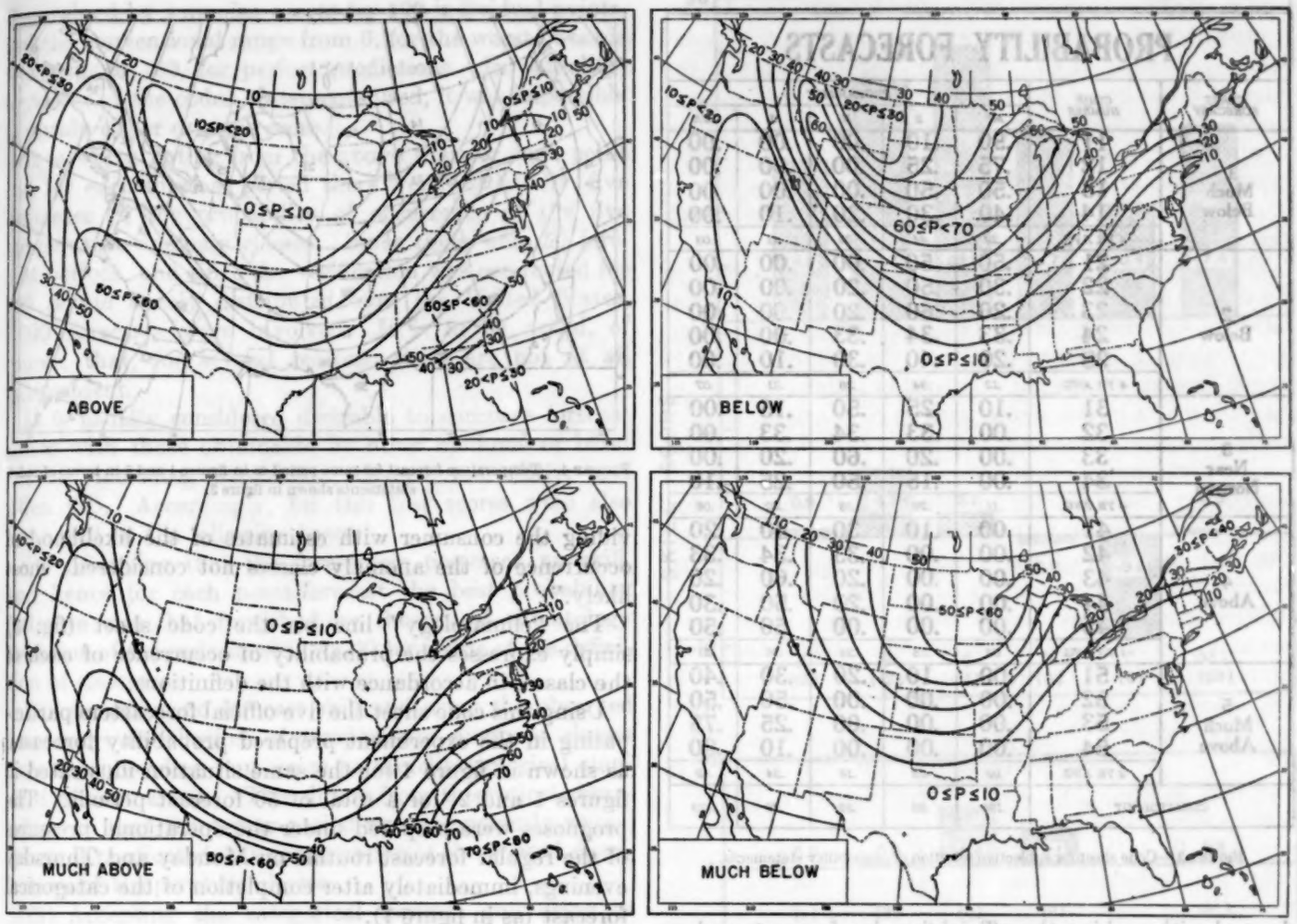

FIGURE 2.—Predicted probabilities of occurrence of separate categories for same period as in figure 1. Probability of *near* normal is calculated as 1.00 minus (sum of probabilities of other four classes).

each of the first three categories just mentioned occurred one-fourth of the 5-day periods within the record studied, while the latter two each occurred one-eighth of the time. These definitions not only simplify the expression of the conventional temperature forecast, as illustrated in figure 1, but also provide a convenient standard of comparison, based on climatology and chance, for measuring forecast skill (see Namias [12], and Brier and Allen [3]).

Objective methods devised for preparing 5-day temperature anomaly forecasts (Martin and Leight [10]), although adaptable, are not at present in suitable form for assessing the likelihood of occurrence of each of the five possible categories. It was therefore decided to experiment with probability forecasting by allowing the official forecaster to stipulate subjective estimates.

For five categories the probability forecast for the United States area can best be presented by a series of charts, as shown in figure 2, instead of the single chart shown in figure 1. A separate map shows for each category the geographical distribution of expected likelihood of occurrence. When prepared in this fashion, care must be taken to insure that at every point the sum of the probabilities of the five classes must be exactly unity. In the illustration shown, the chart for *near* normal is omitted; the probability of *near* normal at any point can be readily computed by subtracting from 1.00 the sum of the probabilities of the other four classes.

In order to simplify the procedure, the forecasters were provided with a code sheet, shown in figure 3, containing 22 selected statements of the probability of occurrence of each of the five temperature anomaly categories shown at the tops of the columns. The first digit of the two-figure code number indicates the "most likely" category, i. e., the conventional categorical forecast, while the second digit increases, essentially, with increasing likelihood of the warmer classes. Obviously, these statements represent a very small sample of the infinite variety of statements which a forecaster might choose subjectively, but it was felt that increasing the number of lines in the table would only serve to complicate the evaluation process and might, at the same time, furnish a spurious indication of the forecaster's capability in delineating the expected probabilities of occurrence. The specific choices were made only after deliberations by the personnel

PROBABILITY FORECASTS

CLASS FORECAST	CODE NUMBER	PROBABILITY				
		MB	B	N	A	MA
1 Much Below	11	.90	.10	.00	.00	.00
	12	.75	.25	.00	.00	.00
	13	.50	.50	.00	.00	.00
	14	.40	.30	.20	.10	.00
	4 YR. AVG.	.22	.44	.20	.11	.03
2 Below	21	.50	.50	.00	.00	.00
	22	.30	.50	.20	.00	.00
	23	.20	.60	.20	.00	.00
	24	.33	.34	.33	.00	.00
	25	.20	.40	.30	.10	.00
	4 YR. AVG.	.12	.34	.26	.21	.07
3 Near Normal	31	.10	.25	.50	.15	.00
	32	.00	.33	.34	.33	.00
	33	.00	.20	.60	.20	.00
	34	.00	.15	.50	.25	.10
	4 YR. AVG.	.11	.29	.28	.26	.06
4 Above	41	.00	.10	.30	.40	.20
	42	.00	.00	.33	.34	.33
	43	.00	.00	.20	.60	.20
	44	.00	.00	.20	.50	.30
	45	.00	.00	.00	.50	.50
	4 YR. AVG.	.03	.16	.24	.36	.21
5 Much Above	51	.00	.10	.20	.30	.40
	52	.00	.00	.00	.50	.50
	53	.00	.00	.00	.25	.75
	54	.00	.00	.00	.10	.90
	4 YR. AVG.	.02	.06	.14	.34	.42
CLIMATOLOGY		.125	.25	.25	.25	.125

FIGURE 3.—Code sheet for subjective selection of probability statements.

charged with making the official five-day forecasts and, as might be expected, experimentation has led to many suggestions for improvements.

For guidance purposes, the code sheet also included the lines labelled "4-yr avg." and "climatology." The former figures represent the fraction of time during the 4-year period immediately preceding the experiment that each of the classes was observed when a specific one was categorically predicted. It may be of interest to compare these figures with those in table 1 which was similarly computed for the 11-year period from October 1940 through September 1951. The high degree of similarity between the 2 sets of figures demonstrates that real skill is involved in making the conventional categorical forecasts. The actual values show the extent of that skill and, at the same time, emphasize the advantages of providing the consumer with estimates of the likelihood of occurrence of the anomaly classes not considered "most likely."

TABLE 1.—*Frequency of occurrence of temperature anomalies, by class, during the period October 1940 through September 1951 according to anomaly class predicted*

Predicted class	Observed class					
	1-MB	2-B	3-N	4-A	5-MA	Total
1-MB	0.246	0.387	0.212	0.122	0.033	1.00
2-B	.116	.338	.276	.213	.057	1.00
3-N	.053	.247	.295	.305	.100	1.00
4-A	.025	.149	.241	.386	.199	1.00
5-MA	.013	.074	.144	.375	.394	1.00

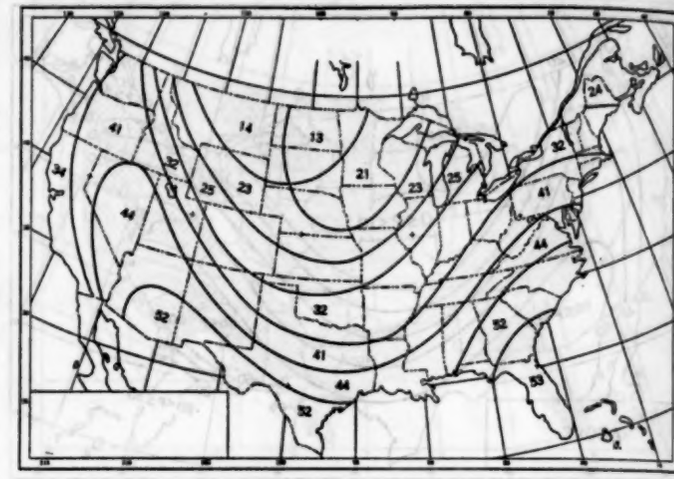

FIGURE 4.—Temperature forecast for same period as in figures 1 and 2 in terms of coded statements shown in figure 3.

The "climatology" line on the code sheet (fig. 3) simply expresses the probability of occurrence of each of the classes in accordance with the definitions.

Using this code sheet the five official forecasters participating in the experiment prepared probability forecasts, as shown in figure 4 for the same situation illustrated in figures 1 and 2, for a total of 50 forecast periods. The prognoses were prepared under the operational pressures of the regular forecast routine on Monday and Thursday evenings, immediately after completion of the categorical forecast (as in figure 1).

METHOD OF VERIFICATION

As proposed by Brier [2], the probability forecasts were verified pointwise by summing over the five categories the squares of the differences between predicted and observed probabilities,

$$S_1=\sum_1^5 (P_f-P_o)^2 \quad (1)$$

where P_f is the probability forecast and P_o is that observed (unity for occurrence and zero for non-occurrence). For each forecast S_1, the sum of the squared errors of the probability estimates, was computed for each of 100 points, converted to a score,

$$S^*=1-\tfrac{1}{2}\,S_1 \quad (2)$$

in order to define a score which increased with increasing success, and a final score,

$$S=\sum_1^{100} S^* \quad (3)$$

was determined. This arbitrarily transformed [2] score,

[2] By reversing the transformations one may easily reconvert the results presented below to the mean squared errors which are perhaps more significant from a statistical point of view.

S, obtained by summing scores for 100 individual points, had the conventional range from 0, for the worst possible forecasts, to 100, for perfect predictions. In actuality, by virtue of the coded statements used, it was impossible to obtain either extreme score.

It is worth noting from the above that for each point and for each forecast period there were, essentially, five estimates of the probability of occurrence of the five temperature anomaly classes. Since there were 50 forecast periods, and since the verification was conducted for 100 points evenly distributed over the United States, 5,000 forecasts were involved. It is to be noted, of course, that, for several reasons, these are not at all independent.

It is usually considered desirable to compare forecast scores with those obtainable by other methods or blind devices, including persistence, chance, etc. (Brier and Allen [3]). Accordingly, for this test scores were also computed on the following bases:

(1) Assuming that the forecasters possessed no skill, and hence for each point-forecast the best probability estimate was that furnished by theoretical climatology (last line of the code sheet in fig. 3) by virtue of the definition of classes.

(2) Assuming no forecast skill and using the observed frequency distribution of temperature anomaly classes over the preceding four years as the climatological standard of comparison. This differs from theoretical climatology in that the 4-year period was anomalously warm; its use is predicated on a continuation of the skewed distribution of temperature classes.

(3) Accepting the categorical forecast and using as probability statement the frequency distribution achieved by forecast class during the previous four years (the lines labelled "4-yr. avg.").

(4) Accepting the categorical prediction and using as probability statement that of "least confidence" (code number 14, 25, 32, 41, or 51).

From the above-mentioned scores and those for the subjective probability predictions various analyses were made of the relative ability of forecasters in estimating likelihood of occurrence (by checking observed frequencies against forecast probabilities), etc.

DISCUSSION OF VERIFICATION SCORES

A summary of the verification scores is shown by the bar graphs in figure 5. The results obtained by the five forecasters participating (labelled "A" through "E"), by the group as a whole ("ALL") and by the "blind" forecasts have been compared to the "expected" and are expressed as skill scores in accordance with the formula:

$$\text{Skill Score}=\frac{S-E}{T-E}\times 100 \qquad (4)$$

where S is the score obtained, E the "expected", and T the maximum score attainable.

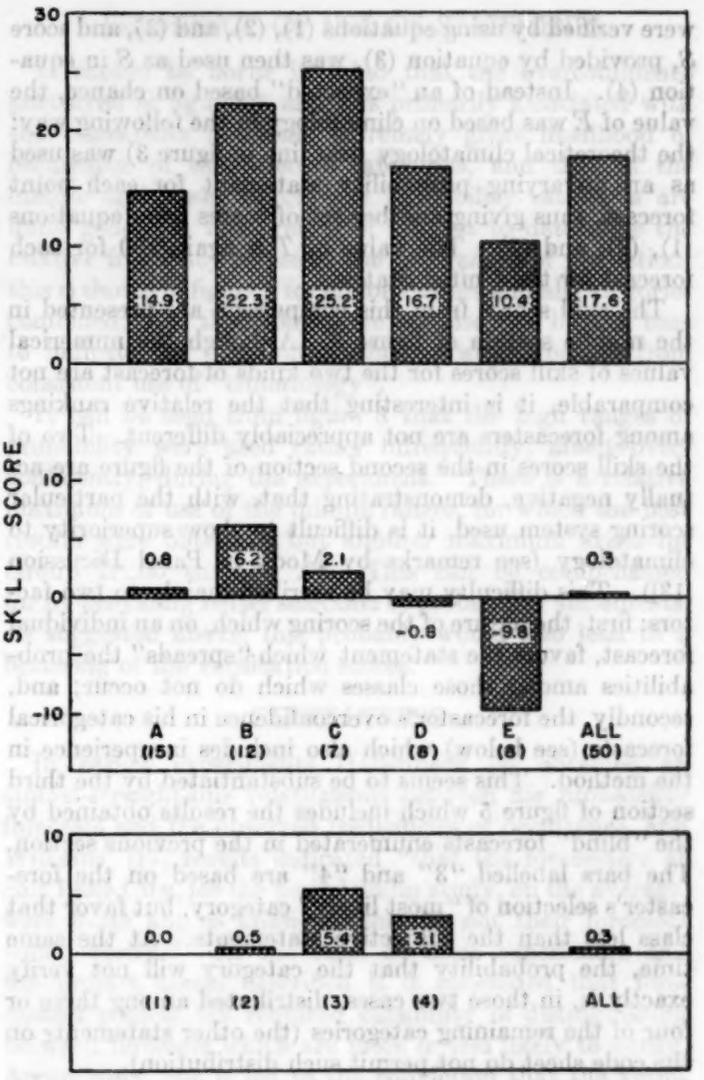

FIGURE 5.—Skill scores obtained by individual forecasters (A, B, C, D, and E) and group as whole (ALL) for categorical forecasts (upper) and for probability statements (middle); numbers in parentheses indicate number of predictions per forecaster. Skill scores obtained by "blind" controls, as enumerated in text (1, 2, 3, and 4) and by group of forecasters as a whole (ALL) are shown at bottom.

The skill scores for the conventional categorical forecasts are shown in the upper part of figure 5. For each forecast period the skill score is regularly computed by taking as S the number of points of 100 distributed over the United States (T) for which the category was predicted correctly. The "expected" is calculated as one-eighth of the number of points for which either *much above* or *much below* is observed [3] plus one-fourth of the remaining points of the total 100. This is the number correct one would most likely have obtained by drawing forecasts randomly from a population distributed in proportion to the defined category distribution.

The forecasts made in terms of probability statements

[3] The choice of "expected" is arbitrary, and is often made in terms of persistence, the distribution of the predicted marginal totals, or a combination of observed and predicted totals for each category; each method has desirable and undesirable characteristics. The "expected" based on the distribution of observed categories, used in routine verification and, therefore, in this study, is independent of manipulation by the forecaster.

were verified by using equations (1), (2), and (3), and score S, provided by equation (3), was then used as S in equation (4). Instead of an "expected" based on chance, the value of E was based on climatology in the following way: the theoretical climatology (last line in figure 3) was used as an unvarying probability statement for each point forecast, thus giving another set of scores from equations (1), (2), and (3). The value of T is again 100 for each forecast for the United States.

The skill scores from this comparison are presented in the middle section of figure 5. Although the numerical values of skill scores for the two kinds of forecast are not comparable, it is interesting that the relative rankings among forecasters are not appreciably different. Two of the skill scores in the second section of the figure are actually negative, demonstrating that, with the particular scoring system used, it is difficult to show superiority to climatology (see remarks by Mook in Panel Dicussion [13]). This difficulty may be ascribed mainly to two factors: first, the nature of the scoring which, on an individual forecast, favors the statement which "spreads" the probabilities among those classes which do not occur; and, secondly, the forecaster's overconfidence in his categorical forecasts (see below) which also includes inexperience in the method. This seems to be substantiated by the third section of figure 5 which includes the results obtained by the "blind" forecasts enumerated in the previous section. The bars labelled "3" and "4" are based on the forecaster's selection of "most likely" category, but favor that class less than the subjective statements. At the same time, the probability that the category will not verify exactly is, in those two cases, distributed among three or four of the remaining categories (the other statements on the code sheet do not permit such distribution).

One might conclude from the success of the "4-yr avg." forecasts (item 3) that statistics of past performance are perhaps the best source of estimates of probability. Obviously, they provide an excellent first approximation to estimates of likelihood of occurrence—which does not imply perfect forecasting. On the contrary, it is recognized that our forecasting ability is far from perfect, and probability statements, such as the automatically-translated "4-yr avg." estimates, supply valuable additional information to the recipient of the categorical forecasts.

It remains to be demonstrated whether or not the forecaster can subjectively improve on the statistics of past performance. The fact that the "least confidence" statements (item 4), while not quite as good as the "4-yr avg." lines, are measurably better than the climatological (items 1 and 2) and subjective (ALL) estimates buttresses the contention that the scoring is aided by the "spreading" of likelihood of occurrence among all categories. (It should be stressed that over a sufficiently long period the best scores will derive from probability estimates which are in accord with the observed frequency distributions. The success of the "4-yr avg." follows from its derivation from relatively long-term records.) If any improvements are to be made subjectively, they must depend on the forecasters' ability to distinguish between situations, i. e., capability in correctly delineating degree of confidence.

ABILITY TO EXPRESS CONFIDENCE

As stated above, each of the 5000 point-forecasts made during the experiment represented five sub-forecasts of the probability of occurrence of each of the temperature anomaly categories ranging from .00 to .90. To measure the forecasters' skill in selecting statements, the predictions were classified into five groups as shown in table 2 with, as an example, the pertinent code numbers (from fig. 3) for the *much above* normal predictions. Analyses were then performed for each participating forecaster and each predicted category to relate confidence, as expressed in the code numbers, to observed frequency of occurrence. The results are summarized in figures 6 and 7.

The data in figure 6 have been plotted at the mid-points of the range groups just defined against the percentage of the point forecasts that the particular category was

TABLE 2.—*Probability forecast groupings for analysis of forecasters' capabilities*

Group	Probability range	Applicable code numbers for forecasts of *much above* normal
I	.00 and .10	11 through 34.
II	.15 through .25	41 and 43.
III	.30 through .40	42, 44, and 51.
IV	.50 and .60	45 and 52.
V	.75 and .90	53 and 54.

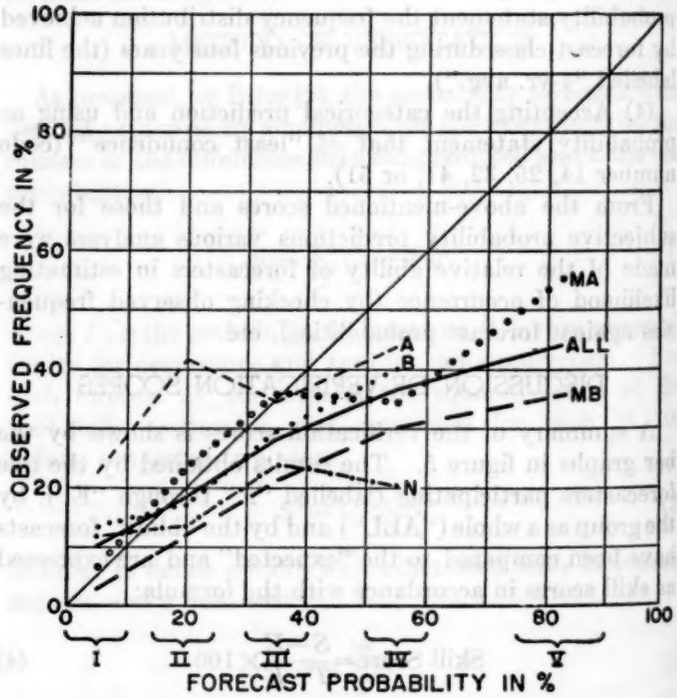

FIGURE 6.—Relationship between forecast probability, plotted at midpoints of range groups indicated by Roman numerals, and observed frequency of occurrence of individual temperature anomaly categories and all categories combined. Perfect probability estimates represented by 45° line.

observed. This has been done for each category for all forecasters combined and, in addition, a composite curve has been drawn for all categories combined. The six curves can also be compared with the 45° line which indicates perfect ability in sorting weather situations into groups for which the forecaster knows the percentage frequency of occurrence.

Inspection of the curves in figure 6 reveals, as might be expected from the figures in table 1, that forecasting the *near* normal category is most difficult. This has also been found to be true in a qualitative fashion by the forecasters themselves, probably because *near* normal is usually observed in strips separating large areas of greater anomaly. Figure 6 also shows marked overconfidence in the higher ranges of estimate for the extreme categories and for *above* normal in the lower ranges. However, it is encouraging to note the distinct upward slope of the curves, showing definite increase of observed frequency with greater confidence. (It might be noted that the lines would be horizontal if there were absolutely no skill and would slope downward to the right with negative skill.)

Similar conclusions can be drawn from figure 7 which combines all temperature categories to show the relationship of predicted vs. observed probability (frequency) by forecaster. As in figure 6, the 45° line of "perfect estimate" and the composite for all forecasters and categories (representing 25,000 point-category forecasts) are included. This figure also contains a horizontal dashed line representing the distribution that might be expected from a random sampling of a population distributed according to the definition of classes.

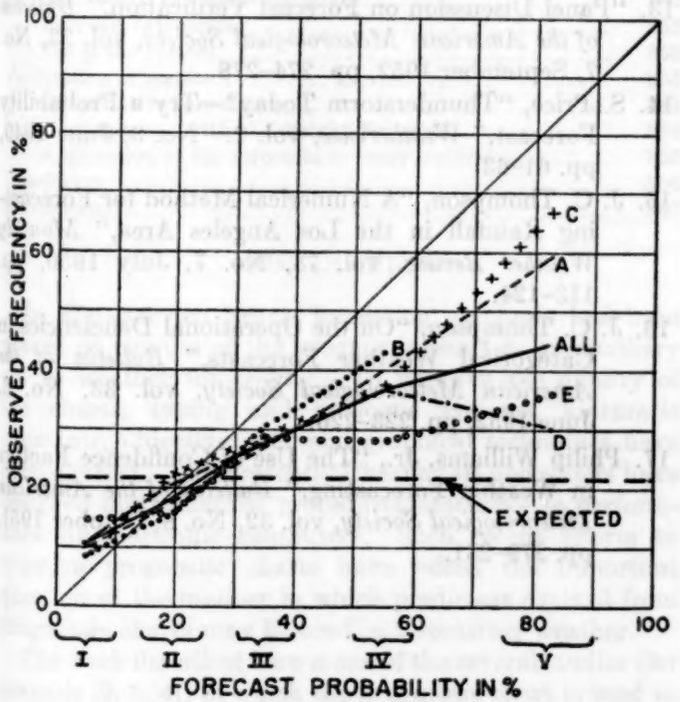

FIGURE 7.—Relationship between forecast probability, plotted at mid-points of range groups indicated by Roman numerals, and observed frequency of occurrence for all temperature categories combined by individual forecaster and group as whole. Perfect estimates shown by 45° line and chance estimates shown by dashed horizontal line.

FREQUENCY OF USE OF STATEMENTS

It should be borne in mind that the overconfidence portrayed in figures 6 and 7 is primarily associated with the statements involving extremely great likelihood of occurrence of the forecast categories, and that in the middle and lower ranges the probability estimates are quite good. It is therefore of interest to determine the relative frequency of use of the five ranges of prediction; this is shown in figure 8 for all forecasters and all categories combined. On this chart there are also two broken bars to indicate the distribution theoretically expected from consistent use of "climatology".

It can be seen from figure 8 that the high ranges of probability were used rather infrequently, albeit overconfidently, during the experiment. There is a relative maximum of use of the middle ranges, for which the best results were obtained, but another maximum exists for Group I: .00 through .10. This can be compensated for by providing better selection of probability statements. As suggested above, this probably would also lead to a bettering of the verification scores.

CONCLUSIONS

In earlier experiments Hallenbeck [9] obtained an almost-straight-line relationship between his probability forecasts and the observed frequencies of occurrence, and Williams' [17] results indicated "that the forecasters at Salt Lake City, for the period under study, on the average, were quite apt to know whether or not their forecasts would verify." On the basis of these experiences and the project herein described it is concluded that forecasters possess the required capability of distinguishing between forecasts which are more or less likely to verify. Accordingly, one is led to the conviction that the verification scores achieved by the "4-yr avg." can be materially

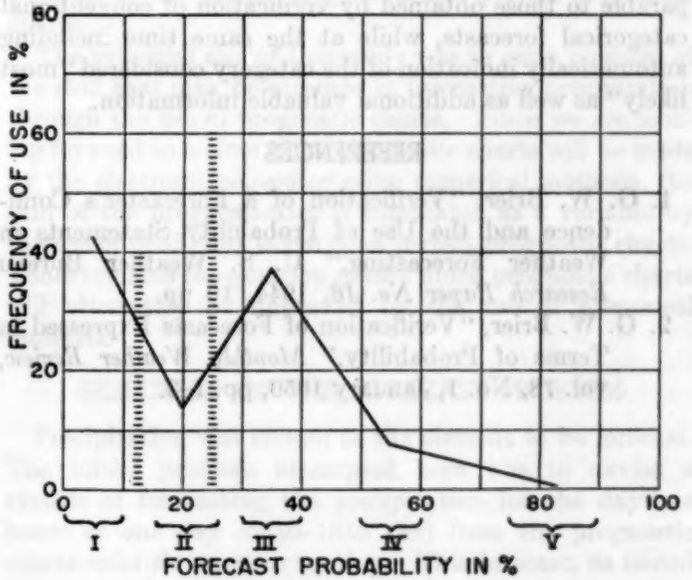

FIGURE 8.—Frequency of use of probability statements as grouped in table 2. Vertical bars indicate forecasting by climatology only.

improved by judicious use of coded statements more carefully contrived.

The improvement of the statements presented for the forecasters' consideration might best be achieved by using the "4-yr avg." lines of figure 3 (or the 11-yr avg. data from table 1) as a guide and introducing into the tabulation estimates involving more reasonable "spreading" of the probability of nonoccurrence of the category considered "most likely". It would also be feasible to include "blank" code numbers (such as 19, 29, etc.) for which the forecaster might specify probability ranges required for a particular forecast problem. In regions dominated by a quasi-stationary front during a forecast period, for example, the forecaster might well wish to assign equal probabilities of cold and warm anomalies, with a minimum probability of *near* normal.

Since the conduct of this experiment demonstrated that the additional labor involved in the preparation of the probability estimates was not great, this scheme is operationally practical at the transmitting end. In fact, the participating forecasters have estimated that the availability of better statements would reduce the time required to an insignificant amount, relatively speaking.

From the consumer's point of view, it seems incontrovertible that the extra information provided by probability statements (Thompson [16])—or even by such statistics as presented in table 1—is of great value. Since it has been demonstrated that the forecasters can, with fair degree of skill, assess confidence in the predictions, this information should be made available to the forecast user.

In conclusion, it is felt that some system of expressing forecasts in terms of probability is practical and extremely desirable. Such estimates can be prepared without undue extra effort on the part of the forecasters and with a fair amount of skill. Furthermore, the form of expression discussed here is susceptible to scoring with results comparable to those obtained by verification of conventional categorical forecasts, while at the same time including automatically indication of the category considered "most likely" as well as additional valuable information.

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FORECASTING WINTER PRECIPITATION 36 TO 48 HOURS IN ADVANCE AT DES MOINES, IOWA

An Experiment Using the Prognostic Chart as a Data Source

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ABSTRACT

To determine the accuracy with which a precipitation forecast can be made from the features of the prognostic charts currently disseminated, an objective forecast system using only those features has been developed for the Des Moines, Iowa, area. As a means of finding predictors, sets of composite sea level and 700-mb. charts were made up for very dry situations and for situations in which heavy precipitation occurred. In the final system, the various predictors are combined in scatter diagrams to give a forecast, comparable in accuracy with that of the district forecast, of the occurrence of precipitation at Des Moines during a 12-hour period beginning 12 hours after the valid time of the 30-hour sea level prognostic chart.

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INTRODUCTION

In the last ten years, increasing emphasis has been placed on the use of the prognostic chart as an auxiliary aid to weather forecasting. To improve the quality of the charts, typing and analogue systems, kinematic equations, objective aids, and graphical techniques have been devised. More recently Charney [1] and others have designed mathematical procedures amenable to performance by electronic computers. Such recent efforts to improve prognostic charts have raised the important question of the manner in which predictors derived from prognostic charts may be used in forecasting weather.

The work described here is one of the several studies (for example [2, 3, 4]) in which the prognostic chart is used as a source of predictors upon which the occurrence of some weather element is dependent. In this study, a forecast system was developed using perfect prognostic charts of the surface and 700-mb. level, that is, actual weather maps but consisting of only those items to be found on currently transmitted prognostic charts. The completed forecast system was tested on an independent series of perfect prognostic charts. This test indicates the degree to which the system is independent of the particular period covered by the charts used in developing the system. A further test was then made using the prognostic charts from the independent series. This test has the purpose of measuring both the skill of the system under actual working conditions and the amount by which the skill drops off due to the lack of identity between features of the actual prognostic and perfect prognostic charts.

The principal aim of this study was to get a measure of the skill that may be attained in forecasting precipitation through the use of prognostic charts. Since we are looking forward to a time when prognostic charts will be made by the electronic computer using numerical methods, the skill of the prognosticator is eliminated as a variable by the use of predictors taken from perfect prognostic charts. There remains the question of how much prognostic charts will ultimately be improved by the use of numerical methods.

SELECTION OF THE FORECAST PROBLEM

Precipitation was chosen as the element to be forecast. The initial problem attempted here was to devise a system of forecasting the precipitation for the daytime hours of one day (0630–1830 CST) from the prognostic charts *valid the previous evening.* This forecast, as issued by the district and local forecasters, is made in the even-

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ing two days earlier from the 1830 CST surface chart and 0900 CST upper air charts. Available to the forecaster are the prognostic 30-hour surface and 36-hour 700-mb. charts valid the following evening at 1830 and 2100 CST, respectively. It is from these prognostic charts that the data for the method to be described are obtained, although in developing the method actual observed charts (perfect prognostics) for those times were used.

Several parts of the United States were considered in selecting a locality for which to forecast. A study by Bristor on the selection of forecast research problems [5] indicated that forecasting aids would be very useful in the region between the Mississippi River and the Rockies. Des Moines was selected within this region because of its central location within its area of service responsibility.

Some thought was given to working out the system so that it would be applicable to all seasons of the year, but because of the many differences between precipitation-producing situations in the warm and cold months, the system constructed applies only to the months of December, January, and February.

FAMILIARIZATION WITH THE AREA

Familiarization with the preciptiation-producing synoptic situations of central Iowa was aided by lists, made for each of the 4 seasons, of 10 dates on which large amounts of precipitation occurred within the selected 12 hours and 10 dates on which there was no precipitation in the Des Moines area. For this purpose 3 months were assigned to each season, e. g., "winter" consists of December, January, and February. In order that the no-precipitation dates should represent exceptionally dry conditions, it was further specified that there be no precipitation in the entire State on that date and none at Des Moines for at least 2 days before and after. Most of the dry days were actually in periods of severe drought. Cases were selected, not from the entire period of record, but only from the period since November 13, 1945, for which map data are available on punched cards.

Although examination of the individual maps was of value in learning to recognize weather potentialities, the possibility remained that important indications beyond the immediate vicinity of the forecast area would go unnoticed. For this reason, the 8 lists of 10 dates described above were submitted to the Weather Bureau's Machine Tabulation Unit where punched cards containing sea level pressure data at 1830 CST and 700-mb. height data at 2100 CST for the western half of the Northern Hemisphere were processed to get average pressure and height values from which composite sea level and 700-mb. charts, for dry and precipitation situations were plotted and analyzed.

COMPOSITE CHARTS

The composite charts for the winter season are shown in figures 1–4. Several important differences between the dry and wet situations are apparent. Dry conditions accompany a strongly developed subtropical high pressure belt between 30° and 40° N., with strong zonal flow from 40° to 55° N., since in this situation, traveling cyclones with their attendant precipitation pass north of the Des Moines area. Heavy precipitation is preceded by a trough aloft west of Des Moines; surface Lows move in from the southwest but pass to the south of the city.

The composite charts can be treated in various ways to bring out their essential differences. Although some differences, such as the path of contours running from Des Moines to the west or the strength of the westerly currents through northern Washington and Montana, are evident at a glance, a more objective means is necessary to bring out the more subtle differences between the two sets of charts. For this purpose the following auxiliary charts were prepared:

a. Pressure difference (fig. 5) and height difference (fig. 6) between dry and precipitation composites. Isopleths of the pressure (or contour) difference form a pattern which may be studied to find axes along which the pressure (or contour) gradient difference between charts is a maximum.
b. Relative topography (mean isotherms) and mean flow between sea level and 700-mb. composites. With these charts, the advection patterns of the sea level to 700-mb. layer may be compared.
c. Sea level and 700-mb. composites of the charts 24 hours earlier than the initial set of charts.
d. Composite pressure and height change in the 24 hours preceding the time of the initial set of charts.

DEVELOPMENT OF THE OBJECTIVE SYSTEM

THE SEARCH FOR PARAMETERS

Initially, the patterns of the sea level and 700-mb. composites and of the auxiliary charts (figs. 1–6) were examined to find parameters related to one or more of the primary precipitation variables: moisture supply, thermodynamic instability, and lifting mechanism. Since only situations of *heavy* precipitation make up the precipitation composites, it was necessary to examine the less homogeneous situations associated with small amounts of precipitation to define additional types of precipitation producers.

The parameters selected are, in general, related to more than one of the primary precipitation variables. This is particularly true in the case of southerly wind components in the lower levels, for not only does the principal moisture source lie to the south, but also southerly winds tend to occur with approaching troughs with whose eastern portions are associated convective instability and several types of lifting mechanism. The lifting mechanism may be upglide of the warm moist air over a slower moving cold airmass, sudden lifting of the warm moist air by a cold front, the pre-frontal squall line, or quite often some less definable process such as might be associated with a great field of divergence in the high levels of the troposphere with upward motion between it and a compensating field of convergence in the lower levels. As shown by Klein [2]

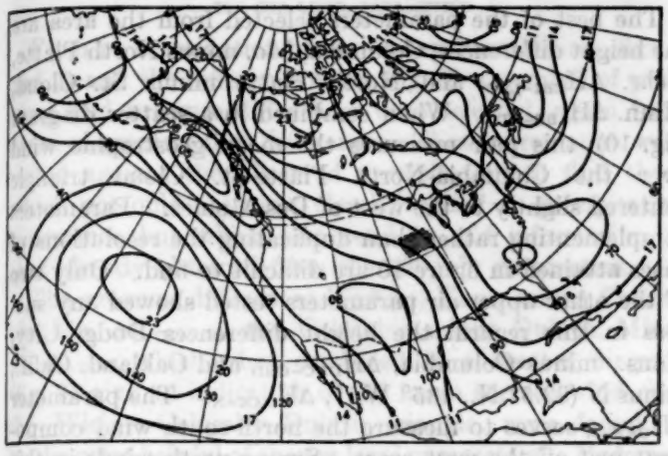

FIGURE 1.—Composite sea level pressure chart for ten winter cases of heavy 12-hour precipitation at Des Moines, Iowa. Isobars are labeled in millibars, hundreds omitted. State of Iowa is indicated by shading.

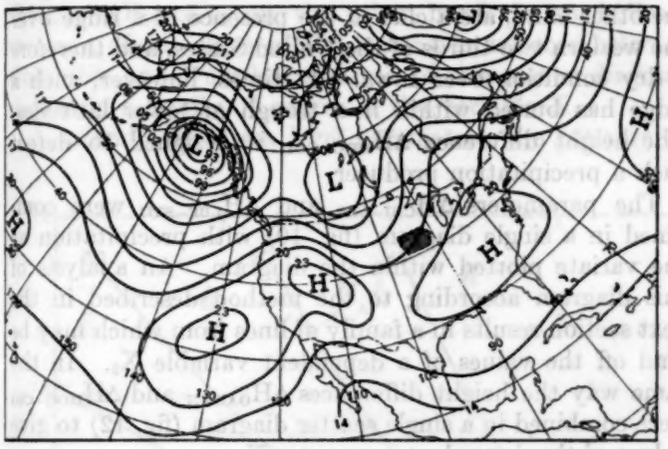

FIGURE 2.—Composite sea level pressure chart for ten winter cases of dry conditions at Des Moines. Isobars are labeled in millibars, hundreds omitted. State of Iowa is indicated by shading.

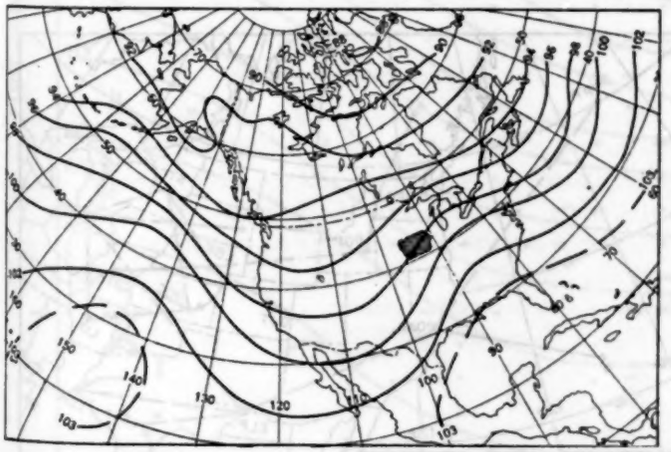

FIGURE 3.—Composite 700-mb. chart for ten winter cases of heavy 12-hour precipitation at Des Moines (same cases used for fig. 1). Contours are in hundreds of feet. State of Iowa is indicated by shading.

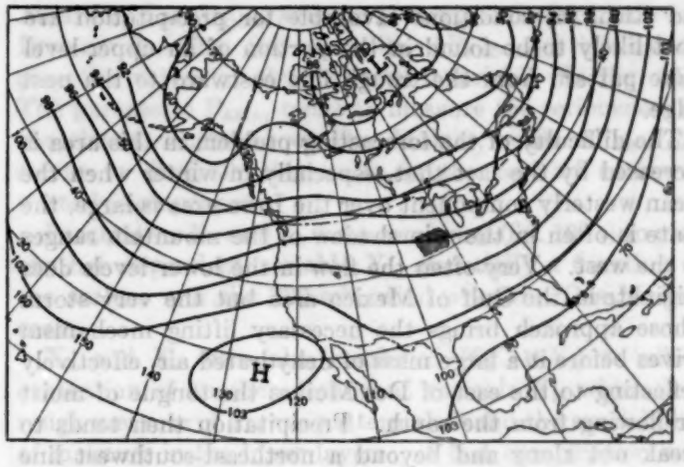

FIGURE 4.—Composite 700-mb. chart for ten winter cases of dry conditions at Des Moines (same cases used for fig. 2). Contours are in hundreds of feet. State of Iowa is indicated by shading.

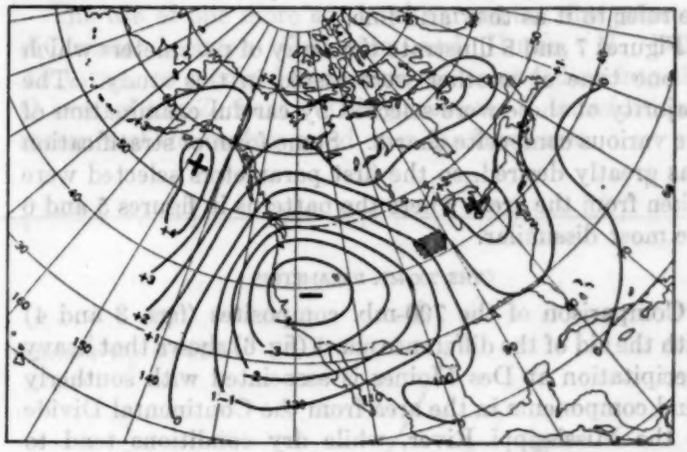

FIGURE 5.—Pressure difference chart, in millibars, computed by subtracting sea level pressure on composite charts for dry conditions (fig. 2) from sea level pressure on composite charts for heavy 12-hour precipitation (fig. 1). State of Iowa is indicated by shading.

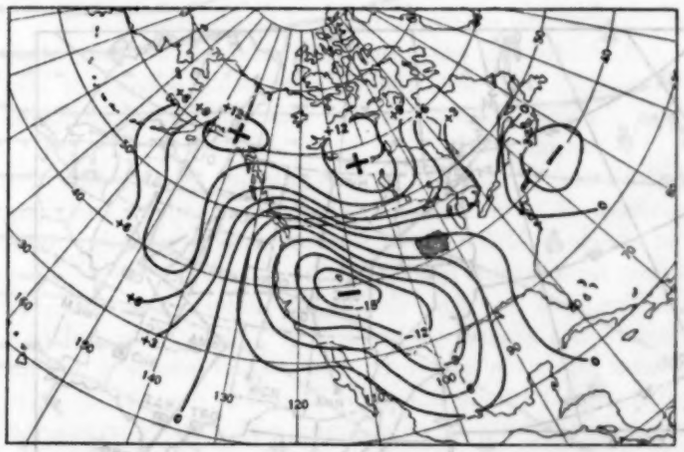

FIGURE 6.—Height difference chart, in hundreds of feet, computed by subtracting 700-mb. height on composite charts for dry conditions (fig. 4) from 700-mb. height on composite charts for heavy 12-hour precipitation (fig. 3). State of Iowa is indicated by shading.

and Riehl [6] conditions favorable for precipitation are most likely to be found in the portion of an upper-level wave pattern from the trough line eastward to the next ridge.

The difficulty of the forecasting problem in this area is increased by the fact that, especially in winter when the mean westerly component over the Iowa area is large, the State is often in the rain shadow of the mountain ranges to the west. Very often the flow in the lower levels does originate in the Gulf of Mexico area but the very storm whose approach brings the necessary lifting mechanism drives before it a large mass of dehydrated air, effectively deflecting to the east of Des Moines the tongue of moist air flowing from the south. Precipitation then tends to break out along and beyond a northeast-southwest line not very far to the east of Des Moines. This line separating the area having little or no precipitation from the area of heavier precipitation is usually so well marked that we refer to it as the "arid line."

Figures 7 and 8 illustrate the array of parameters which at one time or another were tested in this study. The majority of these were selected by careful examination of the various composite charts. Some form of stratification was greatly desired, so the first parameters selected were taken from the areas where the patterns in figures 5 and 6 are most dissimilar.

THE 700-MB. PARAMETERS

Comparison of the 700-mb. composites (figs. 3 and 4) with the aid of the difference chart (fig. 6) shows that heavy precipitation at Des Moines is associated with southerly wind components in the area from the Continental Divide to the Mississippi River, while dry conditions tend to occur when there is west-northwesterly flow in that area and a ridge at 120° W. These observations suggest that a measure of the wind flow in this area should be useful as a predictor.

The best of the parameters selected from the area are the height differences, Columbia, Mo. minus North Platte, Nebr. $\Delta H_{CBI-LBF}$, and North Platte minus St. Cloud, Minn. $\Delta H_{LBF-STC}$. When combined in a scatter diagram (fig. 10), this pair measures the mean geostrophic wind over the Columbia-North Platte-St. Cloud triangle centered slightly to the west of Des Moines. Parameters complementing rather than duplicating the resolutions of cases attained in figure 10 are difficult to find. Only two of the other upper air parameters tested showed any success in this regard, the height differences Dodge City, Kans., minus Columbia, $\Delta H_{DDC-CBI}$, and Oakland, Calif., minus N (32.5° N., 135° W.)*, ΔH_{OAK-N}. The parameter ΔH_{OAK-N} serves to measure the north-south wind component just off the west coast. Strong north winds in this area are associated with developing trough situations inland which in turn often produce precipitation over Iowa. Strong southerly components just off the west coast, on the other hand, are a clue to the presence of a ridge over the western two-thirds of the United States, and therefore a dry condition over Iowa. At times, however, such a ridge has buried within it a trough at lower latitudes. The height difference $\Delta H_{DDC-CBI}$, is designed to detect such a precipitation producer.

The parameters $\Delta H_{CBI-LBF}$ and $\Delta H_{LBF-STC}$ were combined in a single diagram (fig. 10) with precipitation as the variate plotted within the diagram. An analysis of this diagram according to the method described in the next section results in a family of lines from which may be read off the values of a dependent variable X_2. In the same way the height differences ΔH_{OAK-N} and $\Delta H_{DDC-CBI}$ were combined in a single scatter diagram (fig. 12) to give values of the dependent parameter X_4.

*Point N, during the period of the observations used in this study, was the location of Ship N. On December 6, 1953, Ship N was moved to 31° N., 140° W. Therefore, from maps after that date the 700-mb. height for use in determining ΔH_{OAK-N} should be interpolated for the former location.

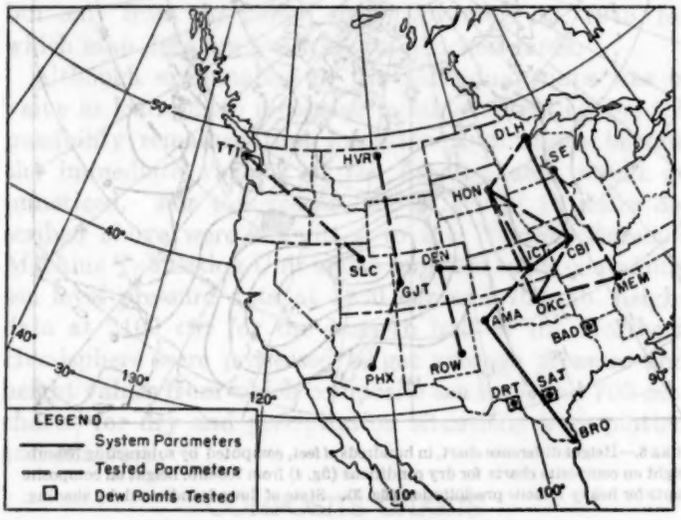

FIGURE 7.—Map of sea level parameters used in the system or tested during the investigation. Joined points indicate pressure difference parameters.

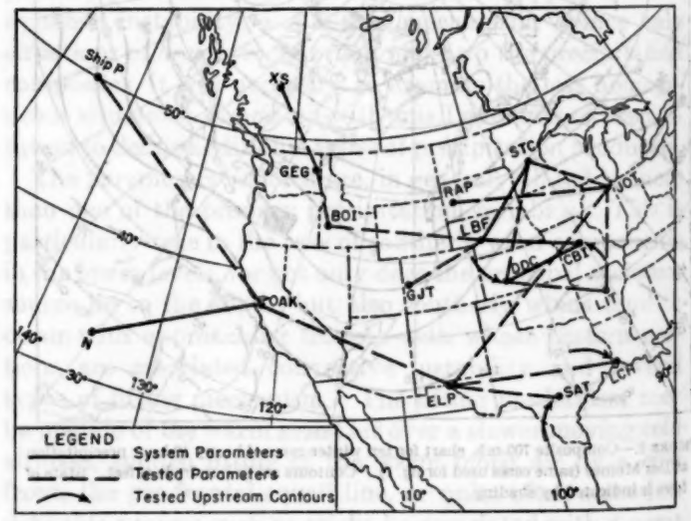

FIGURE 8.—Map of 700-mb. parameters used in the system or tested during the investigation. Joined points indicate height difference parameters.

THE SEA LEVEL PARAMETERS

From an examination of the sea level composites (figs. 1 and 2) and the difference chart (fig. 5) a number of pressures and pressure differences were selected, again from areas of greatest flow difference. These parameters were tested against the observed precipitation to find those which not only are most closely related to precipitation occurrence but which also tend to *add* information to that already obtained from the 700-mb. parameters.

The pressure differences Wichita, Kans. minus Columbia, Mo. $\Delta P_{ICT-CBI}$, and Columbia minus Duluth, Minn. $\Delta P_{CBI-DLH}$, which when combined in a scatter diagram (fig. 9) give an indication of the mean surface wind over the Wichita-Columbia-Duluth triangle, were found to be the most helpful of the sea level parameters. However, each of these two pressure differences has a special significance. $\Delta P_{ICT-CBI}$ is a timing, or "cut-off", parameter testing whether a storm is approaching or is no longer a threat. $\Delta P_{CBI-DLH}$, on the other hand, is an indirect measure of the slope of the isentropic surfaces between Columbia and Duluth. Analysis of this scatter diagram results in a family of curves of the variable X_1.

A second pair of sea level parameters, the pressure at Amarillo, Tex. P_{AMA}, and the pressure difference between Brownsville, Tex. and Amarillo, $\Delta P_{BRO-AMA}$, is used to give the values of the dependent variable X_3 (fig. 11). The parameter P_{AMA}, tends to measure the seriousness of the threat southwest of Des Moines, while $\Delta P_{BRO-AMA}$ serves to diminish this value in the case of excessive westerly components.

Parameters X_1 and X_2 were combined (fig. 13Y_1) to give another dependent variable Y_1, essentially a function of the surface and the 700-mb. wind over the Des Moines area.

X_3 and X_4 were also combined (fig. 13Y_2) to allow evaluation of another dependent variable Y_2, which is a rough measure of a wave pattern aloft and the availability of moisture in the lower layers. A last combination was made of Y_1 and Y_2 as dependent parameters, again with precipitation as the plotted variate, to form the Z chart (fig. 14).

The use of one more sea level parameter, the pressure difference between Columbia and Huron, N. Dak. $\Delta P_{CBI-HON}$, is required to resolve the cases falling into the Q area of the Z chart. This parameter is an additional measure of the surface wind over the Iowa area.

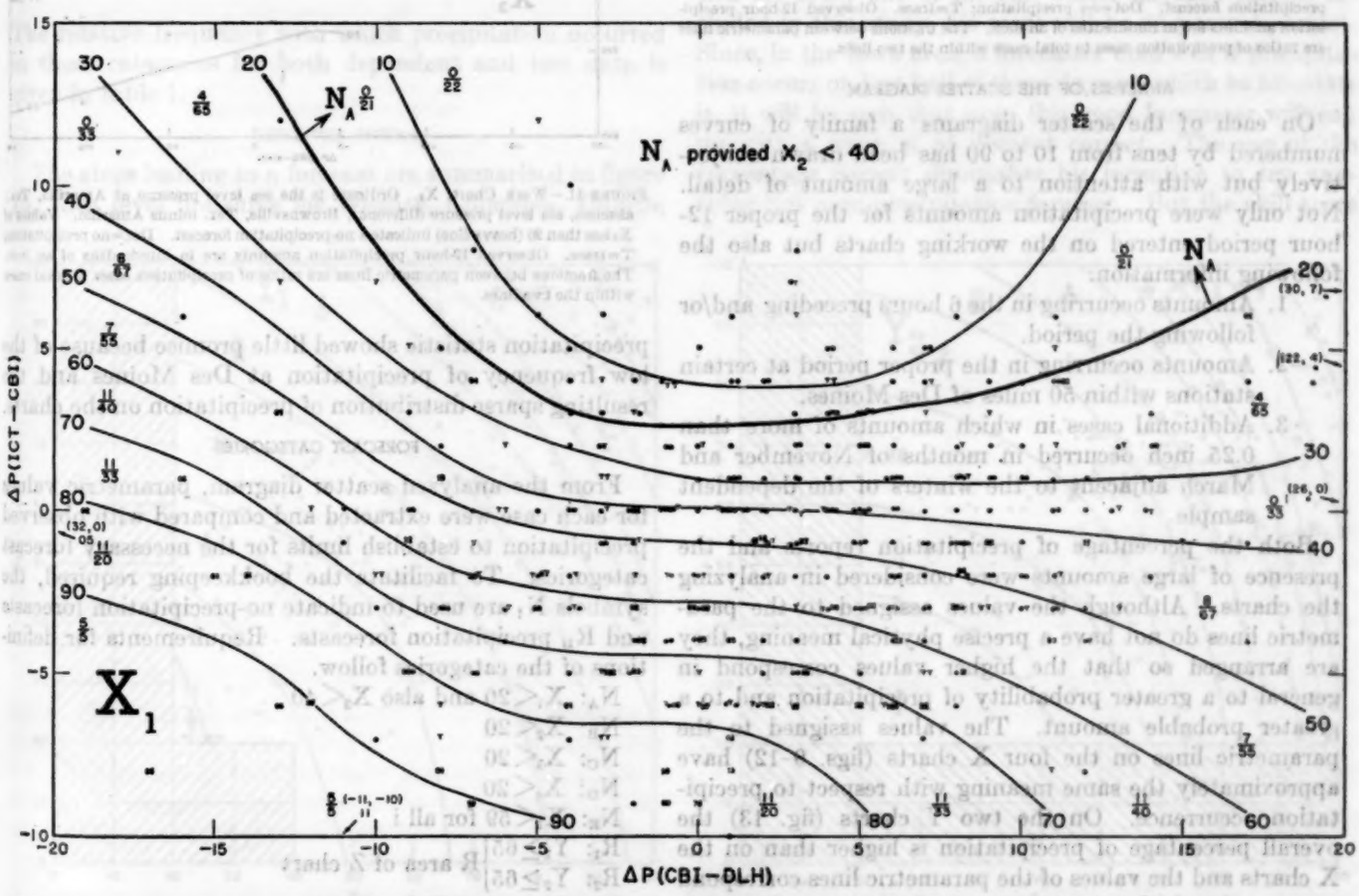

FIGURE 9.—Work Chart: X_1. Ordinate is the sea level pressure difference, Wichita, Kans. minus Columbia, Mo.; abscissa, sea level pressure difference, Columbia, Mo. minus Duluth, Minn. Values of X_1 less than 20 (heavy line) indicate a no-precipitation forecast provided X_2 (fig. 10) is less than 40. Dot=no precipitation; T=trace. Observed 12-hour precipitation amounts are in hundredths of an inch. The fractions between parametric lines are ratios of precipitation cases to total cases within the two lines.

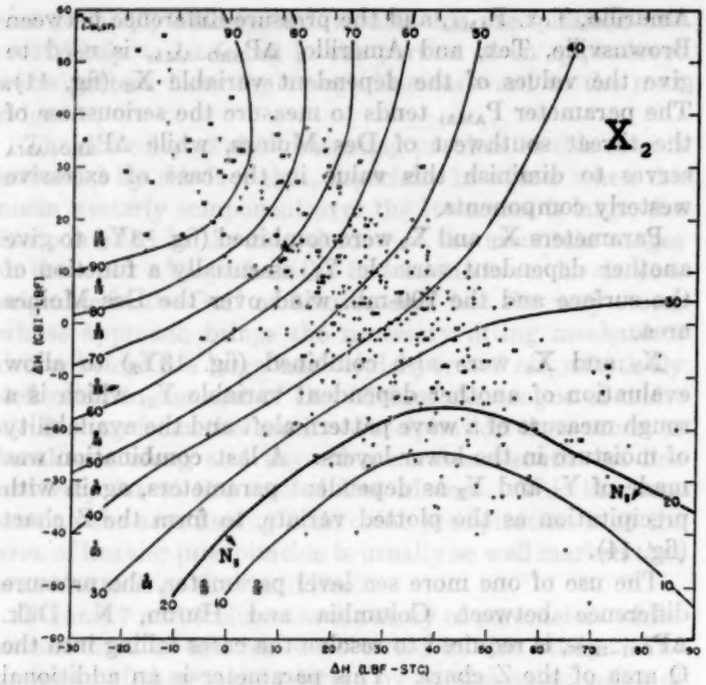

FIGURE 10.—Work Chart: X_2. Ordinate is the 700-mb. height difference Columbia, Mo. minus North Platte, Nebr.; abscissa, 700-mb. height difference, North Platte, Nebr. minus St. Cloud, Minn. Values of X_2 less than 20 (heavy line) indicate a no-precipitation forecast. Dot=no precipitation; T=trace. Observed 12-hour precipitation amounts are in hundredths of an inch. The fractions between parametric lines are ratios of precipitation cases to total cases within the two lines.

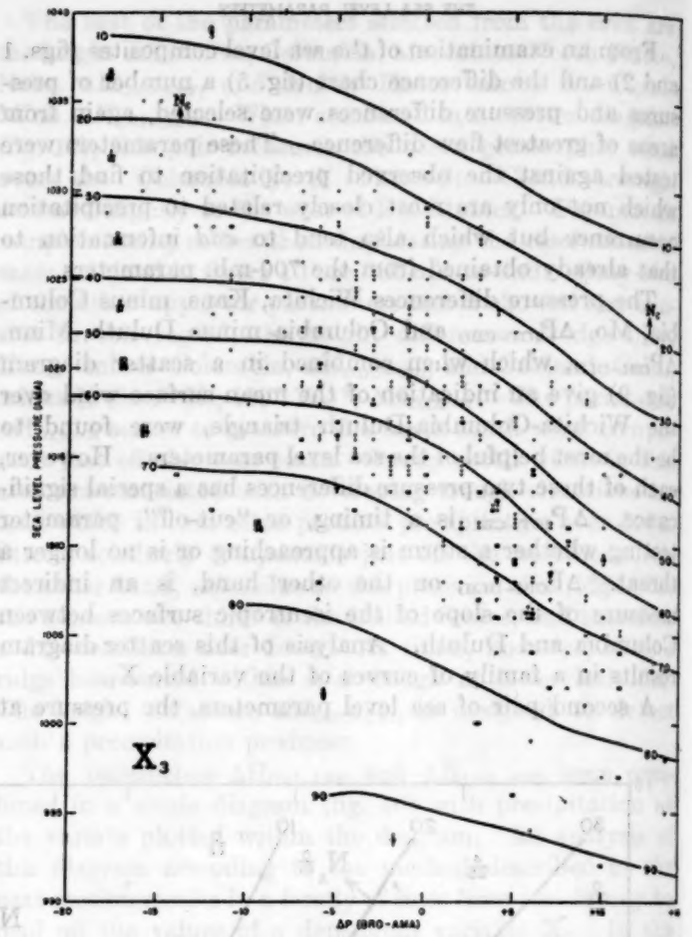

FIGURE 11.—Work Chart: X_3. Ordinate is the sea level pressure at Amarillo, Tex.; abscissa, sea level pressure difference, Brownsville, Tex. minus Amarillo. Values of X_3 less than 20 (heavy line) indicate a no-precipitation forecast. Dot=no precipitation; T=trace. Observed 12-hour precipitation amounts are in hundredths of an inch. The fractions between parametric lines are ratios of precipitation cases to total cases within the two lines.

ANALYSIS OF THE SCATTER DIAGRAM

On each of the scatter diagrams a family of curves numbered by tens from 10 to 90 has been drawn subjectively but with attention to a large amount of detail. Not only were precipitation amounts for the proper 12-hour period entered on the working charts but also the following information:

1. Amounts occurring in the 6 hours preceding and/or following the period.
2. Amounts occurring in the proper period at certain stations within 50 miles of Des Moines.
3. Additional cases in which amounts of more than 0.25 inch occurred in months of November and March adjacent to the winters of the dependent sample.

Both the percentage of precipitation reports and the presence of large amounts were considered in analyzing the charts. Although the values assigned to the parametric lines do not have a precise physical meaning, they are arranged so that the higher values correspond in general to a greater probability of precipitation and to a greater probable amount. The values assigned to the parametric lines on the four X charts (figs. 9–12) have approximately the same meaning with respect to precipitation occurrence. On the two Y charts (fig. 13) the overall percentage of precipitation is higher than on the X charts and the values of the parametric lines correspond to somewhat higher percentages and amounts of precipitation. Attempts made to analyze the charts with families of lines defined with respect to just one type of precipitation statistic showed little promise because of the low frequency of precipitation at Des Moines and the resulting sparse distribution of precipitation on the charts.

FORECAST CATEGORIES

From the analyzed scatter diagram, parametric values for each case were extracted and compared with observed precipitation to establish limits for the necessary forecast categories. To facilitate the bookkeeping required, the symbols N_1 are used to indicate no-precipitation forecasts and R_1, precipitation forecasts. Requirements for definitions of the categories follow.

N_A: $X_1 < 20$ and also $X_2 < 40$
N_B: $X_2 < 20$
N_C: $X_3 < 20$
N_D: $X_4 < 20$
N_E: $X_i < 59$ for all i
R_1: $Y_1 \geq 65$ } R area of Z chart
R_2: $Y_2 \geq 65$ }
N_Z: N area of Z chart
N_Q: Q area of Z chart and $\Delta P_{CBI-HON} > 0$
R_Q: Q area of Z chart and $\Delta P_{CBI-HON} \leq 0$

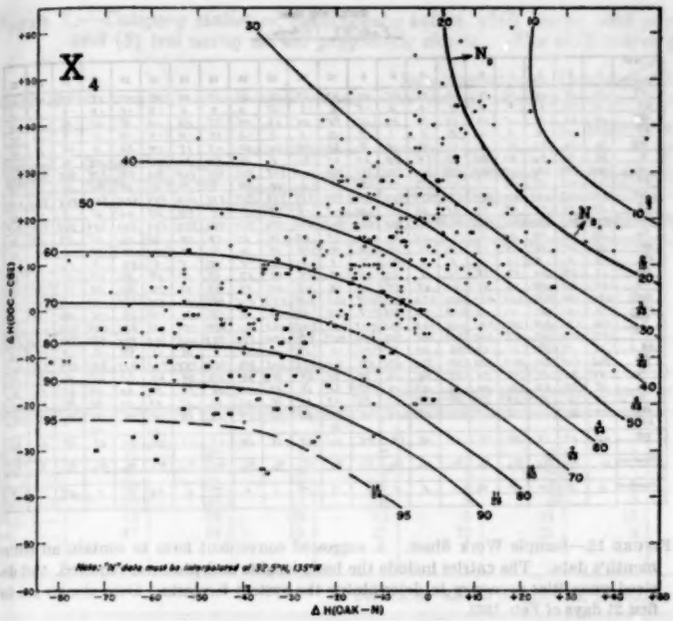

FIGURE 12.—Work Chart: X_4. Ordinate is the 700-mb. height difference Dodge City, Kans. minus Columbia, Mo.; abscissa, 700-mb. height difference, Oakland, Calif. minus N, 32.5°N., 135°W. (former location). Values of X_4 less than 20 (heavy line) indicate a no-precipitation forecast. Dots=no precipitation; T=trace. Observed 12-hour precipitation amounts are in hundredths of an inch. The fractions between parametric lines are ratios of precipitation cases to total cases within the two lines.

The relative frequency with which precipitation occurred in these categories for both dependent and test data is given in table 1.

USING THE SYSTEM

The steps leading to a forecast are summarized in figure 15. Sea level pressures for Wichita, Columbia, Duluth, Brownsville, Amarillo, and Huron and 700-mb. heights for Columbia, North Platte, St. Cloud, Oakland, point N (32.5° N., 135° W.), and Dodge City must be interpolated from the prognostic charts. For more than one-third of the cases, a forecast of N_i (i=A, B, C, D or E) is given by the value of one or more of the X parameters and the process need be carried no further. The R_1 and R_2 forecasts (about one-eighth of all cases) follow directly from the values of the Y parameters. About one-half of all the cases must be carried into the Z chart.

Figure 16 is a sample work sheet illustrating the manner in which the data can be arranged for daily use and monthly tabulation. Some of the steps are omitted when the forecast is reached at an early stage.

VERIFICATION OF RESULTS

Two of the more usual scores used in verifying forecasts are the percentage correct and the skill score. Although both of these scores have certain advantages each has serious deficiencies when used in testing systems such as this. The percentage correct has the disadvantage of being deceptively high in the regions where precipitation is infrequent. For example, if one forecasts no precipitation for every one of the 722 winter daytime periods included in this study, his score will be 85 percent correct. Since, in the Iowa area, a forecaster does well if precipitation occurs on just half of those days on which he forecasts it, it will be seen that even this good forecaster will end up with a score of 85 percent correct. The use of the percentage correct diminishes his incentive to try anything but a no-precipitation forecast. But the skill score

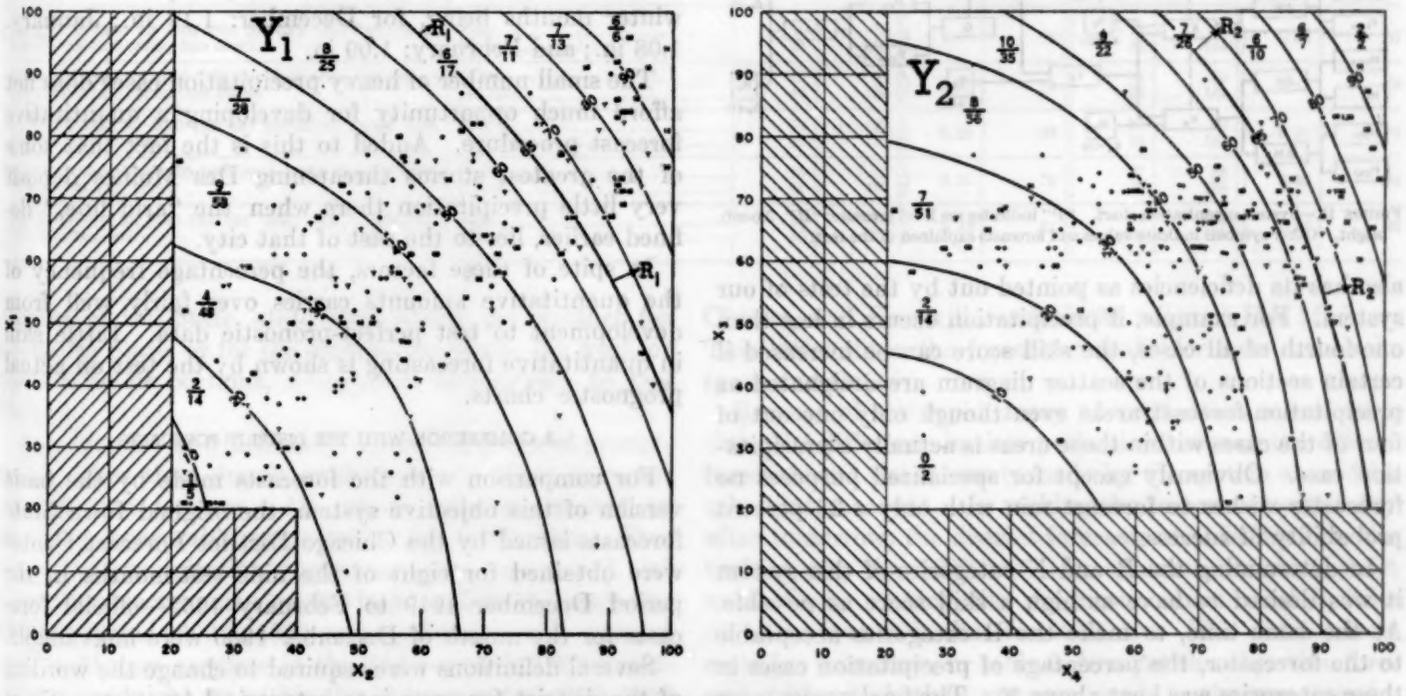

FIGURE 13.—Work Charts: Y_1 and Y_2. Ordinates are X_1 and X_3, and abscissae, X_2 and X_4, respectively. Shaded areas indicate values which were previously eliminated as no-precipitation forecasts on the basis of individual X_i. Dot=no precipitation; T=trace. Observed 12-hour precipitation amounts are in hundredths of an inch. The fractions between parametic lines are ratios of precipitation cases to total cases within the two lines

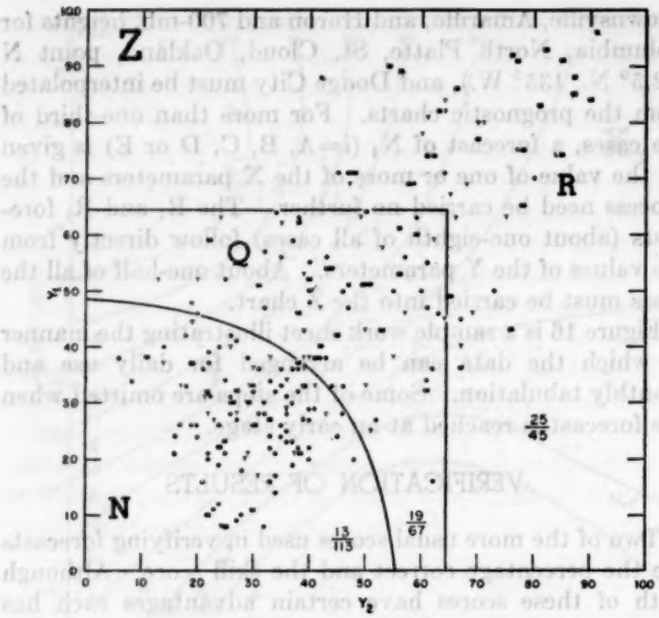

FIGURE 14.—Work Chart: Z. Ordinate and abscissa are Y_1 and Y_2 respectively. The N area indicates a no-precipitation forecast; the R area, a precipitation forecast. The Q area indicates a precipitation forecast unless $\Delta P_{CBI-HON}$ is greater than zero. Dot = no precipitation, T = trace. Observed 12-hour precipitation amounts are in hundredths of an inch. Fractions are ratios of precipitation cases to total cases within each area.

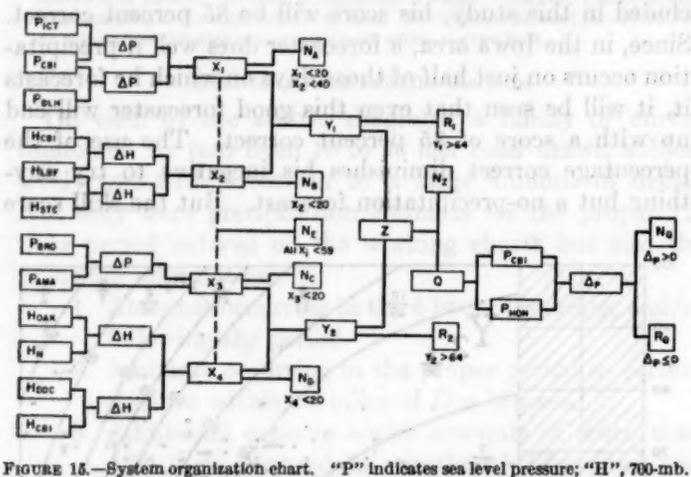

FIGURE 15.—System organization chart. "P" indicates sea level pressure; "H", 700-mb. height. Other symbols indicate values and forecasts explained in the text.

also has its deficiencies as pointed out by the tests of our system. For example, if precipitation occurs in less than one-fourth of all cases, the skill score can be increased if certain sections of the scatter diagram are designated as precipitation-forecast areas even though only one out of four of the cases within those areas is actually a precipitation case. Obviously except for specialized purposes no forecaster wishes to forecast rain with only a 25 percent probability of success.

In determining the R and N categories of this system it was desired to have as high a skill score as possible. At the same time, to make the R catagories acceptable to the forecaster, the percentage of precipitation cases in these categories was kept above 50. The final percentages for the principal R categories, R_1 and R_2, indicate a

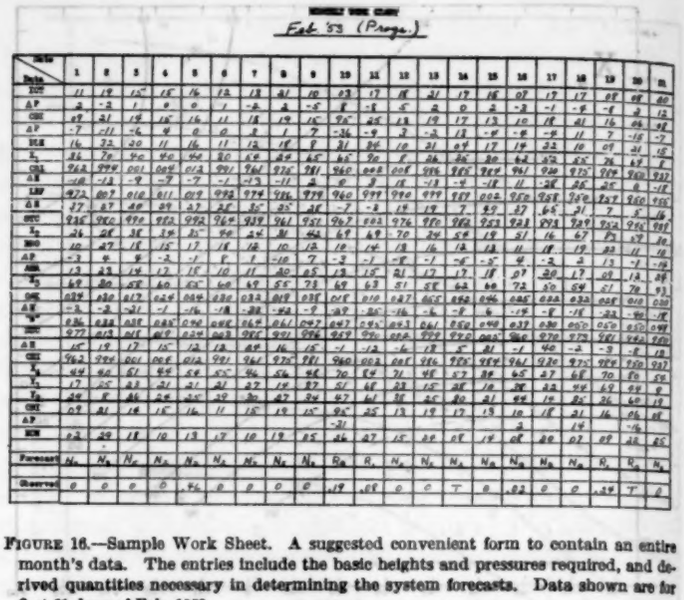

FIGURE 16.—Sample Work Sheet. A suggested convenient form to contain an entire month's data. The entries include the basic heights and pressures required, and derived quantities necessary in determining the system forecasts. Data shown are for first 21 days of Feb. 1953.

decrease in precipitation frequency from 56 percent in the basic data to 42 percent in the test using perfect pronostics (see table 1). Skill scores attained by this system with the developmental data and when applied to independent and actual prognostics are also shown in table 1.

QUANTITATIVE FORECASTING

Included in table 1 is a breakdown, by quantity of precipitation, of the cases of measurable rain falling into each forecast category. Large amounts are infrequent in winter at Des Moines, the normal precipitation for the winter months being, for December: 1.19 in.; January: 1.08 in.; and February: 1.09 in.

The small number of heavy precipitation cases does not afford much opportunity for developing a quantitative forecast procedure. Added to this is the fact that some of the greatest storms threatening Des Moines deposit very little precipitation there when the "arid line," defined earlier, lies to the east of that city.

In spite of these factors, the percentage frequency of the quantitative amounts carries over fairly well from development to test perfect-pronostic data. Little skill in quantitative forecasting is shown by the test on actual prognostic charts.

A COMPARISON WITH THE DISTRICT FORECASTS

For comparison with the forecasts made by the basic version of this objective system, the original Iowa State forecasts issued by the Chicago District Forecast Center were obtained for eight of the nine test months in the period December 1949 to February 1952—official forecasts for the month of December 1950 were unavailable.

Several definitions were required to change the wording of the district forecasts into categorical forecasts. Since Des Moines lies near the center but in the southwest

TABLE 1.—*Category statistics, contingency tables, skill scores, and percent correct for (1) development data, (2) test using "perfect" prognostics, and (3) test using actual prognostic charts. The skill scores given are calculated by the common definition of skill over chance*

Development cases, December 1945, December, January, February 1946-49

Forecast group	Total cases	No rain or trace	Measurable rain									
			Number of cases	Percent of total cases	0.01–0.09 inches		0.10–0.24 inches		0.25–0.49 inches		≥0.50 inches	
					Number	Percent	Number	Percent	Number	Percent	Number	Percent
NABCD	63	63	0	0								
NB	73	73	0	0								
NE	113	100	13	12	11	10	2	2				
NQ	34	30	4	12	1	3	2	6	1	3		
BE-S	45	20	25	56	9	20	8	18	2	5	6	13
BQ	33	18	15	45	12	36	1	3	1	3	1	3

Observed	Forecast: Rain	Forecast: No rain	Forecast: Total
Rain	40	17	57
No rain	38	266	304
Total	78	283	361

Skill score: 0.50.
Percent correct: 85.

Test cases—perfect prognostics, December 1949, December, January, February 1950-53

Forecast group	Total cases	No rain or trace	Measurable rain									
			Number of cases	Percent of total cases	0.01–0.09 inches		0.10–0.24 inches		0.25–0.49 inches		≥0.50 inches	
					Number	Percent	Number	Percent	Number	Percent	Number	Percent
NABCD	75	70	5	7	4	6	1	1				
NB	63	61	2	3	2	3						
NE	88	83	5	6	4	5	0	0	1	1		
NQ	36	33	3	8	2	5	0	0	1	3		
BE-S	52	30	22	42	6	11	10	19	4	8	2	4
BQ	47	34	13	27	10	21	2	4	1	2		

Observed	Forecast: Rain	Forecast: No rain	Forecast: Total
Rain	35	15	50
No rain	64	247	311
Total	99	262	361

Skill score: 0.35.
Percent correct: 78.

Test cases—actual prognostics, December 1949, December, January, February 1950-53

Forecast group	Total cases	No rain or trace	Measurable rain									
			Number of cases	Percent of total cases	0.01–0.09 inches		0.10–0.24 inches		0.25–0.49 inches		≥0.50 inches	
					Number	Percent	Number	Percent	Number	Percent	Number	Percent
NABCD	57	47	10	18	9	16	1	2				
NB	66	63	3	5	3	5						
NE	125	110	15	12	5	4	5	4	4	3	1	1
NQ	44	37	7	16	3	7	3	7	1	2		
BE-S	36	27	9	25	6	17	2	5	0	0	1	3
BQ	33	27	6	18	2	6	2	6	2	6		

Observed	Forecast: Rain	Forecast: No rain	Forecast: Total
Rain	15	35	50
No rain	54	257	311
Total	69	292	361

Skill score: 0.11.
Percent correct: 75.

TABLE 2.—*Comparison of objective and district forecasts for about eight of the test months*

Forecast used	Verifying by precipitation at Des Moines, 0600–1800 CST					Verifying by precipitation at Des Moines midnight to midnight, or at stations within 35 miles, 0600–1800 CST			
		Forecast: Rain	Forecast: No rain	Skill score	Percent correct	Forecast: Rain	Forecast: No rain	Skill score	Percent correct
Objective forecast for 0600–1800 CST day after tomorrow; latest data-1230 CST surface chart.	Rain	10	24	0.08	73	15	43	0.06	67
	No rain	40	162			35	143		
District forecast for 0600–1800 CST day after tomorrow; latest data 1830 CST surface chart.	Rain	10	24	0.07	72	19	39	0.15	69
	No rain	42	160			33	145		
District forecast for 0600–1800 CST tomorrow; latest data 1830 CST surface chart.	Rain	14	21	0.22	78	24	36	0.31	76
	No rain	31	172			21	157		
Objective forecast for 0600–1800 CST tomorrow; latest data 2100 CST 700-mb. chart.	Rain	26	9	0.33	75	37	23	0.36	74
	No rain	51	152			40	138		
District forecast for 0600–1800 CST today; latest data 0030 CST surface chart.	Rain	24	11	0.40	81	35	25	0.45	80
	No rain	35	170			24	156		

quarter of the State, statements about the weather for the entire State, or for the central, the south, the west, or the southwest portions, were taken as applying to Des Moines.

Any forecast in which no mention was made of precipitation other than drizzle or flurries was taken as a no-precipitation forecast. All others were interpreted as requiring measurable precipitation for verification. Two classes of precipitation occurrence were recognized: (a) A measurable amount (>0.005 inch) at Des Moines in the 12-hour period 0600 to 1800 CST; (b) A measurable amount at Des Moines anytime in the 24-hour period from midnight to midnight, or within the 12-hour period 0600–1800 CST at any two of four Iowa stations—Ames, Dexter, St. Charles, and Knoxville—within 35 miles of Des Moines. This latter gives the forecaster credit for near misses in space and time.

Because of the rapid decay of verification scores with time, the difference in time projection between the official forecasts and the forecasts made by the system should be taken into account. In making the forecasts for the day after tomorrow, the district forecaster has before him the surface map for 1830 CST. In contrast, the last chart available in making the prognostic chart used by the objective system is that for 1230 CST. The district forecasts for tomorrow, in table 2, bracket the objective forecast with which they are compared, in the one case by being made without use of the 2100 CST 700-mb. chart and

in the other case by having the advantage of information on the 0030 CST surface chart.

It can be seen in table 2 that the variation in the scores is definitely a function of the projection time of the forecast. There is little to indicate a significant difference between the objective method and the district forecast except perhaps when credit is given for near misses. However, this alternative definition of the occurrence of precipitation was made on the recommendation of a district forecaster as a means of giving credit for what the forecaster feels is a satisfactory job done when the projection time is as long as 36–48 hours. It is quite likely that his forecast is designed with such a definition in mind while the objective system is specifically designed to forecast only for the 12-hour period at Des Moines.

Thus we reach the same conclusion as that of most other objective forecast studies. It is possible to devise an objective forecast system, based on a small number of fairly crude parameters, that will attain very nearly the same degree of success as that of an experienced and able forecaster, but it is difficult, even with a very complex system, to exceed his record in the mean. This is particularly true if the forecaster is aware of the principles upon which the system is based.

APPLICATION OF THE FORECASTS TO OTHER STATIONS

There often arises the important question of how large an area is really being forecast for successfully by a system which, like this one, depends on parametric data from stations far from the point of the forecast. One might also ask whether the point for which the system was designed lies in the center of the area and, if not, whether there is not some other point nearer the center for which the system forecasts with greater skill. It was relatively simple to verify the forecasts of precipitation for Des Moines against the precipitation observed at surrounding stations. A first group of stations was selected and from the results, a second group was added to the list as follows:

First group	*Second group*
Chicago, Ill.	Indianapolis, Ind.
Moline, Ill.	Madison, Wis.
Minneapolis, Minn.	Omaha, Nebr.
Sioux City, Iowa	Grand Island, Nebr.
Kansas City, Mo.	Wichita, Kans.
St. Louis, Mo.	Oklahoma City, Okla.
	Little Rock, Ark.
	Springfield, Mo.
	Columbia, Mo.

The application of the Des Moines forecasts to other stations indicates a rapid falling off of skill to the north (fig. 17). The skill scores tend to be higher at Moline than at Des Moines, and remain at a high level to the south even as far away as Little Rock.

If the results shown in figure 17 are reliable, we are led to conclude that objective forecast systems may very well cover geographically uniform areas as large as 100,000 square miles. Thus a limited number (perhaps 30 or 40) of carefully designed systems could be used to forecast precipitation during a particular period for the entire country.

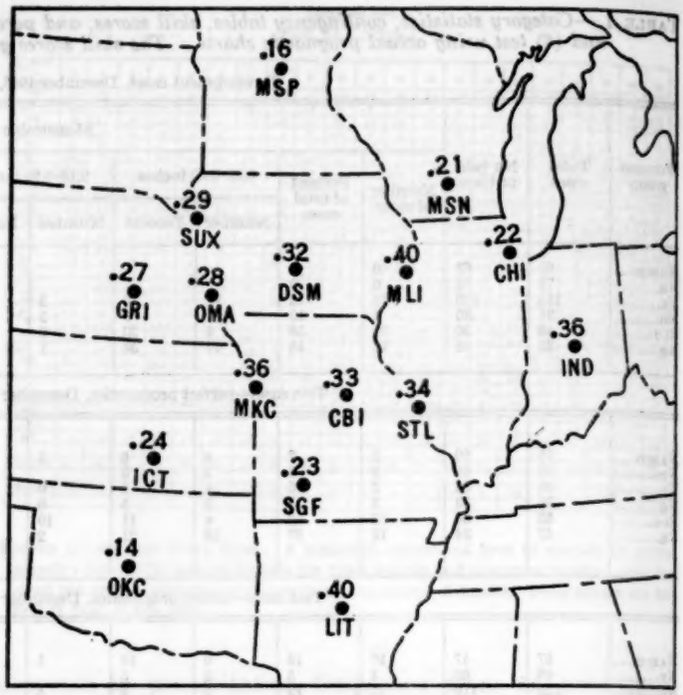

FIGURE 17.—Skill scores attained at various points in the Midwest when forecasts for Des Moines, made by applying the system to data from perfect prognostic charts for the 12 test months in the period, December 1949 to February 1952, are verified against the precipitation occurring at the indicated stations.

CONCLUSION

The simplicity of the system and of the parameters involved might make the reader wonder whether better results could not be obtained through some elaboration. Much time was spent in attempting to improve the results by using a variety of parameters from synoptic charts available to the forecaster or taken from the prognostic chart. Although many types of parameters used in other objective methods were tested, their use did not increase the skill already attained. Another question might arise with respect to the omission of parameters from upper levels other than 700 mb. It was thought inadvisable to use parameters from prognostic charts which, like those for the 500-, 400-, 300-, and 200-mb. levels, have been constructed for only short, irregular periods, because the skill of such parameters could not be adequately tested.

The primary aim of this work was to find a means by which the features of the prognostic charts currently issued could be used to forecast precipitation. That the flow pattern can have such an ability has been demonstrated, at least with the perfect prognostic. However, the fact that the skill score of the system diminishes so greatly when it is tested upon actual prognostics, indicates that the average skill of prognosticators is not great enough

at present to allow optimum use of a system such as this. There are several ways in which prognostic charts may be improved. Among these are more careful selection and training of prognosticators, and improvement of the methods they utilize.

As matters now stand, the skill of the system when tested upon parameters taken from actual prognostics is sufficiently mediocre to suggest that it might be more expedient to bypass the prognostic chart by using parameters taken from the maps available to the forecaster at the time he is making his forecast. This is the type of objective technique used by Schmidt [7, 8] in several recent papers. After such a system had been developed to its fullest extent, an attempt could be made to improve the results by applying parameters taken from prognostic charts available to the forecaster. In this way, at least the main portion of the system would not be affected by the uncertainties of the prognostic procedure.

At present it seems likely that the most promising means of improving the prognostic chart is through the use of numerical methods now being developed to solve physical equations with the aid of the electronic computer. Since the product of numerical methods may be in the form of the future distribution of quantities such as vertical motion directly associated with the precipitation process, it is not unlikely that the precipitation forecast of the future will be completely objective—produced by the computer directly from the raw data.

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THE WEATHER AND CIRCULATION OF NOVEMBER 1953[1]

A Month of Contrasting Regimes

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TWO CONTRASTING CIRCULATION TYPES

The large-scale circulation in mid-troposphere changed markedly over much of the Northern Hemisphere between the first and second halves of November 1953. The differing circulation regimes which prevailed in the two halves of the month are illustrated by the 15-day mean 700-mb. charts in figure 1. The chart for November 1–15 (fig. 1A) shows a pattern of fairly rapid zonal flow with approximately sinusoidal waves of relatively small amplitude from the east coast of Asia eastward to the Atlantic, while somewhat lower index conditions prevailed over much of Europe and Asia. The wave length at middle latitudes was fairly uniform from the western Pacific trough eastward to the trough along the east coast of the United States. However, the Atlantic region was dominated by a deep trough south of Greenland longitudinally superimposed on the subtropical ridge in mid-Atlantic. This pattern was associated with well-marked confluence of cold air currents moving southeastward out of northern Canada and warm air currents moving northeastward from the western Atlantic. The very fast flow across the northeast Atlantic and northern Europe and the long half wave length at higher latitudes between the Atlantic trough and the Eurasian ridge are characteristic downstream features of such large-scale confluence zones (e. g. [1]).

By the second half of November radical readjustments in the wave pattern had taken place as the western Pacific trough strengthened and moved farther eastward off the Asiatic coast (fig. 1B). The circulation over the Pacific now became one vast cyclonic whirl of westerly winds as a single Pacific low cell deepened over the Aleutians. The rapid deepening of the Asiatic coastal trough at this season of the year is a normal feature of the circulation (see [2] pp. 28–29) associated with radiational cooling of the huge Asiatic continent in fall and strengthening of the frontogenetical and cyclogenetical field along the Asiatic coast. However, several outbreaks of abnormally cold Siberian air this November were apparently instrumental in creating the intense cyclonic circulation shown

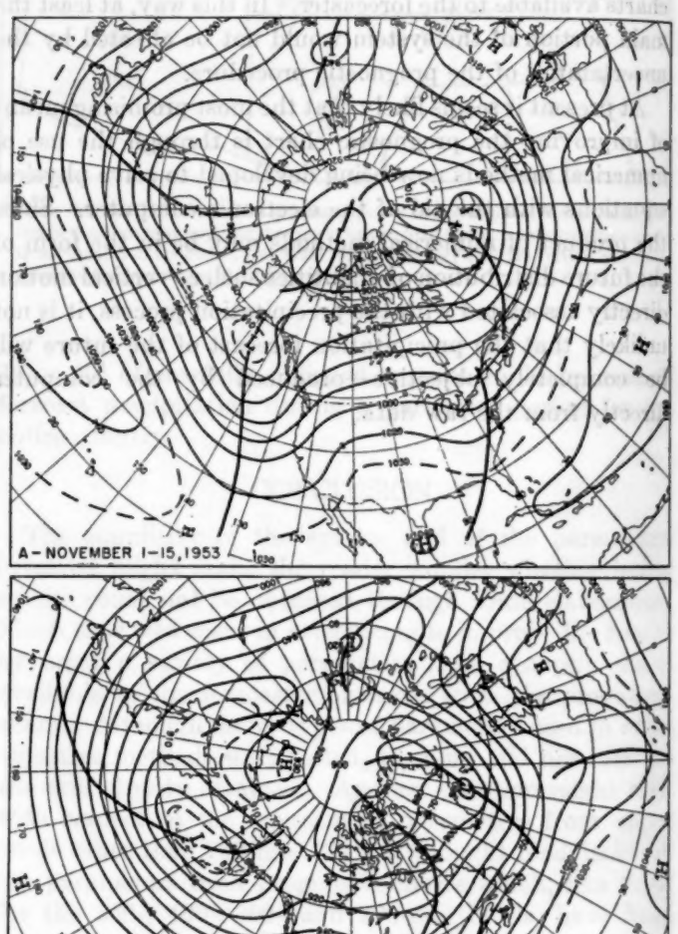

FIGURE 1.—Fifteen-day mean 700-mb. height contours (labeled in tens of feet) for (A) November 1-15 and (B) November 16-30, 1953, showing two contrasting circulation regimes. Note especially the change during the month from two troughs to a single deep trough over the Pacific and the development of a trough over central North America in the second half of the month.

[1] See Charts I-XV following p. 378 for analyzed climatological data for the month.

in figure 1B. This major deepening over the west central Pacific was accompanied by filling of the eastern Pacific trough and development of a weak ridge along the west coast of North America and a trough over central sections of North America. Note the considerable asymmetry of the wave between the western Pacific and central North America, i. e., the very short half wave length on the east side of the ridge over western North America as compared with the very long half wave length on the west side. This asymmetry was probably a result of a combination of at least two effects. One was the generation of cyclonic vorticity by deepening storms as they approached the Aleutians after developing in the strong frontal zone just off the Asiatic coast. This would forestall ridge development to a point farther downstream than would be expected by conservation of absolute vorticity. The effect of the Rockies on a strong westerly current was most likely responsible for the short half wave length east of the ridge. Klein [3] has demonstrated that such short half wave lengths are to be expected when the mid-latitude westerlies are strong across the ridge over western North America.

Development of a trough over central North America brought about a lengthening of the wave length and the termination of confluence over the Atlantic. As a result the westerlies over the Atlantic weakened and a trough developed at middle and lower latitudes in the eastern part of the ocean. Additional marked circulation changes over Europe and Asia accompanied the transitions in the Atlantic and farther upstream. Briefly, the major changes were (1) filling of the central Mediterranean trough, (2) development of a meridional ridge over western Europe which had apparently retrograded from Eurasia, (3) retrogression and development to higher latitudes of a trough over Eurasia, and (4) strengthening of westerlies over Siberia.

Thus it is evident that a virtual hemisphere-wide adjustment in circulation took place between the first and second halves of this November. Although such changes have been observed to take place in almost any month of the year, recent data of Namias [4] indicate that the period October to November is one of the more likely times of the year for the occurrence of marked breaks in circulation. It is worthy of note that Namias' data were for North America and vicinity only, but one might infer that more remote portions of the hemispheric circulation would also undergo reversals. Indeed circulation changes in recent late autumns (e. g., 1951 [5] and 1952 [6]) as well as this year have involved the greater part of the hemispheric wave pattern.

EFFECTS ON STORMINESS AND PRECIPITATION OVER THE UNITED STATES

This month's contrasting circulation regimes had a pronounced influence on cyclone tracks and precipitation during the two halves of November. These effects are illustrated by figures 2 and 3. In figure 2 are shown the tracks of centers of cyclones at sea level over the United States and vicinity. These tracks were copied directly from Chart X, but separation according to the two halves of November gives a clear picture of the great differences in cyclonic activity. Note in figure 2A the marked concentration of cyclone paths in southern Canada and the virtual absence of cyclones over most of the United States. The only cyclone in the first half of the month which had a major effect within the country was the severe East Coast storm which originated in the Gulf of Mexico on the 4th, traveled up the Atlantic coast in a cyclonically curved arc, and then moved inland across New York State and Lake Huron. This storm produced record early season snowfall at many middle Atlantic stations, heavy rains along the immediate coast and in much of New England, and severe gales and high tides along the coast from southern New England to New Jersey [7]. This cyclone was associated with the mean trough located along the east coast in the first half of November (fig. 1A). Meanwhile the absence of cyclones throughout the remainder of the United States was attributable to prevailing anticyclonic circulation over middle sections of the country.

Figure 2B portrays the increase in storminess over the United States associated with the well-developed trough over central North America in the second half of November (fig. 1B). No well-defined prevailing track is discernible, but the major storms most characteristic of the new circulation regime were those which originated in Nevada on the 17th and 20th and brought widespread precipitation of fairly sizeable amounts to much of the country.

Comparison of figures 3A and 3B shows the trend toward more precipitation over the United States accompanying the changing circulation pattern and increasing storminess after the middle of November. Note in figure 3A the large areas (perhaps 75 percent of the United States) where precipitation totaled less than 50 percent of normal. Especially remarkable was the large region in the Midwest where no measurable precipitation fell during the entire 15 days. This regime of predominantly subnormal precipitation over the United States is characteristic of periods when the main westerly belt and cyclone track are north of the United States, anticyclonic conditions prevail over the western and central portions of the country, and troughs are located near each coast. Heavier-than-normal precipitation was mainly confined to areas on the Atlantic and Pacific coasts on the east side of the mean troughs in figure 1A. Other areas of heavier-than-normal precipitation, such as those in east Texas, New Mexico, Colorado, and central portions of the Plains, do not appear to fit in with the mean flow pattern or with the lack of cyclones in those areas. This precipitation was related to upslope easterly wind components and to smaller-scale upper trough phenomena

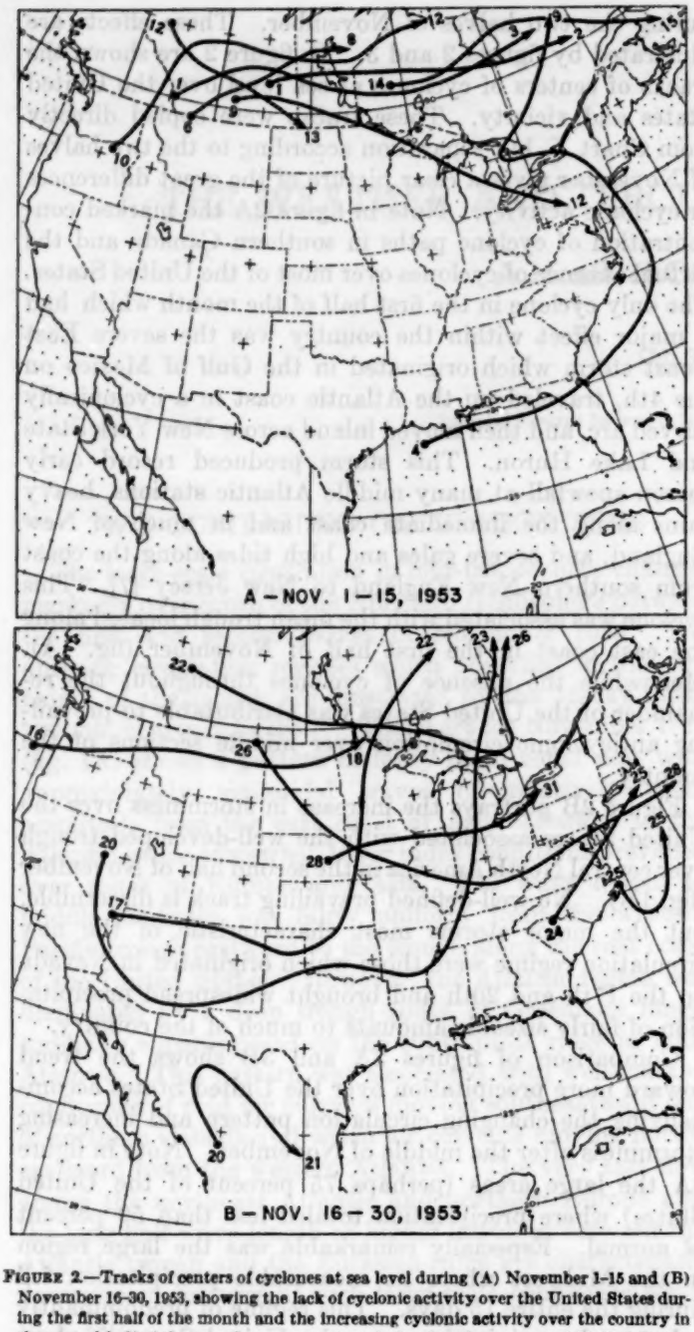

FIGURE 2.—Tracks of centers of cyclones at sea level during (A) November 1–15 and (B) November 16–30, 1953, showing the lack of cyclonic activity over the United States during the first half of the month and the increasing cyclonic activity over the country in the second half of the month as a mean trough developed over central United States.

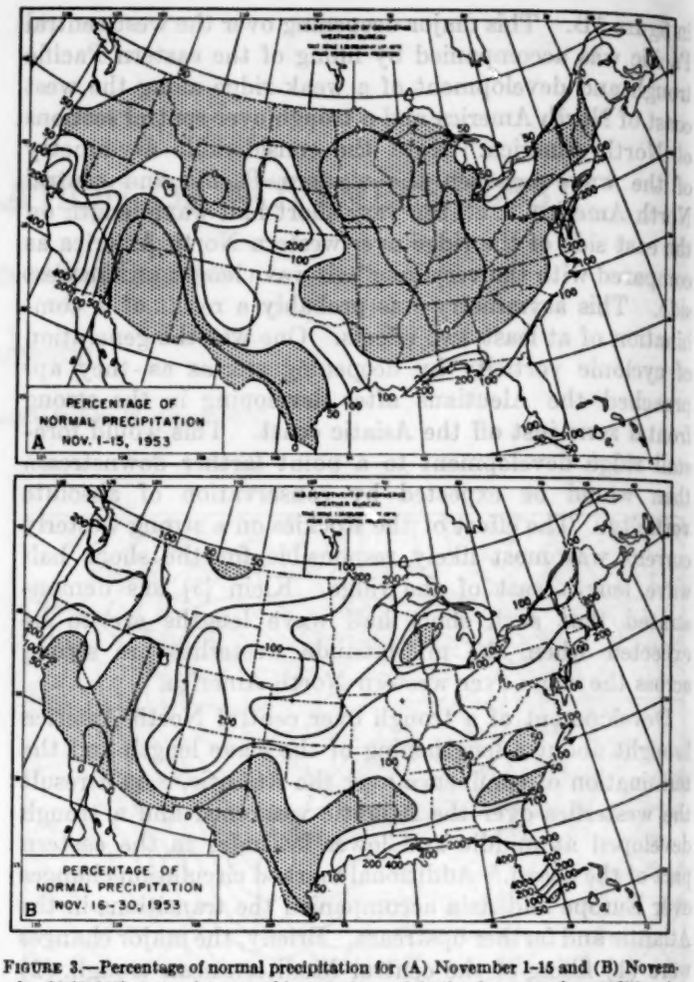

FIGURE 3.—Percentage of normal precipitation for (A) November 1–15 and (B) November 16–30, 1953, portraying general increase in precipitation from very dry conditions in many areas in the first half of the month to more normal precipitation amounts in the second half. These changes are related to basic changes in circulation and storminess shown in figures 1 and 2.

which lasted only a few days and were smoothed out of the large-scale flow pattern.

In figure 3B the areas totaling less than 50 percent of normal occupy only a small portion of the country. In fact, in almost half of the nation precipitation exceeded normal amounts. This was related to intensifying trough conditions and increasing storminess over the central United States as already mentioned. It is somewhat surprising, though, that much of the eastern half of the United States had subnormal precipitation amounts even though this region was located under southwesterly flow in advance of the mean upper-level trough. It is believed that this was due to an insufficient supply of moisture from the Gulf of Mexico over this region. Indicative of this were the absence of a well-developed Bermuda High cell and the existence of flat westerly flow along the Gulf coast which tended to transport Gulf air masses almost directly eastward across the extreme Southeast. As a result, much of the Gulf Coast States and Florida received rather substantial amounts of rainfall in this period while amounts farther north were considerably lighter. Nevertheless, the most important consideration in comparing figures 3A and 3B is that precipitation generally increased over large sections of the country, some of which were still feeling the effects during early November of the long-period drought of summer and fall (See e. g., [8].).

One of the most interesting changes in precipitation regimes occurred over the Far West where California received excessive precipitation in the first half of November while the Northwest had subnormal amounts. Figure 3B shows a virtually complete reversal during the second half of the month with less than 50 percent of normal over most of California and amounts in excess of normal over all of Washington and Oregon and most of Idaho. These differences were closely related to the differing

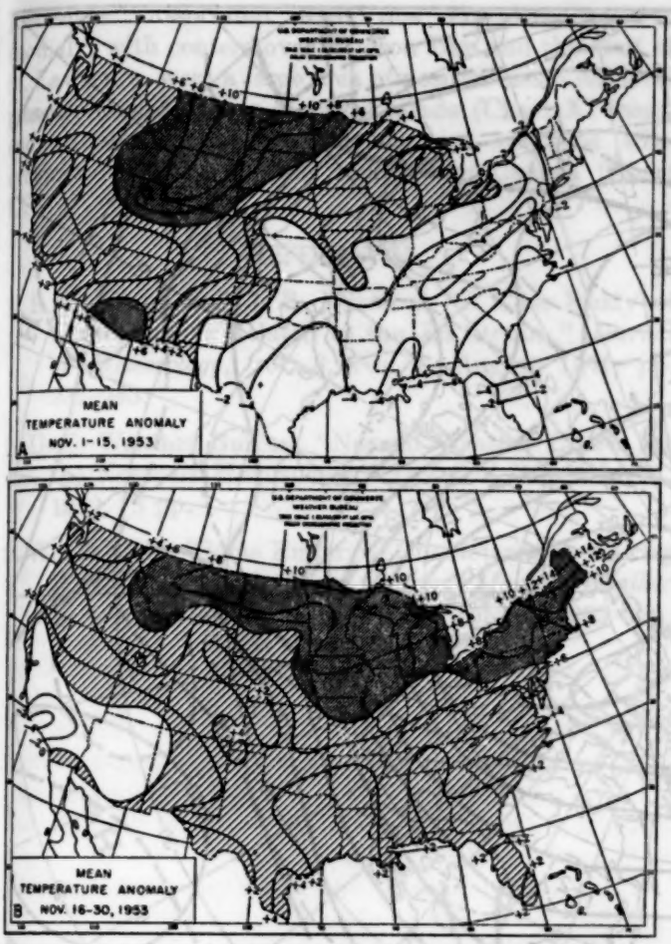

FIGURE 4.—Mean surface temperature anomaly in °F. for (A) November 1-15 and (B) November 16-30, 1953. Note general warming over East and South and some cooling over Far Southwest as circulation regime changed. Northern border sections from Lakes westward remained very warm throughout month owing to the prevalence of mild Pacific air masses brought eastward by zonal flow patterns shown in figure 1.

character of circulation over the West Coast States where precipitation is greatly influenced by orographic effects. Figure 1A portrays a basically meridional flow to the east of the deep trough in the eastern Pacific. This flow was perpendicular to the California coast, but made much less of an angle with the Washington-Oregon coastline. In addition, the greatest cyclonic curvature in the flow existed over California. In the second half of November (fig. 1B) strong zonal flow was dominant along the west coast with the strongest belt of westerlies striking Washington and Oregon. Characteristically these winds, which were perpendicular to the coast and the mountain ranges, brought copious precipitation to the Northwest. Meanwhile the mean flow in California was anticyclonic and parallel to the coast and the mountains, thereby allowing only considerably subnormal amounts of precipitation.

DIFFERING TEMPERATURE REGIMES

Mean temperatures for the two halves of November also showed some significant differences as a result of the changing circulation regimes. From November 1 to 15 below normal temperatures were experienced in almost half of the country from the Northeast southward to Florida and southwestward to the Southern Plains (fig. 4A). This cold weather was associated with the well-defined trough near the east coast and northerly components of flow over the eastern half of the nation. Weaker-than-normal westerly flow over the South Central States allowed for penetration and lingering of cold continental polar air which moved southward east of the Mississippi Valley. Across the north, where westerlies were stronger, warm Pacific air masses frequently spread eastward through the Northern Plains and into the Lakes Region following cold air outbreaks in the East. Furthermore, the Lakes Region and Upper Mississippi Valley were also kept warm by return flow of continental polar air which had been heated over the Southeast. Pacific air masses reaching the west coast in the first half of the month had trajectories which traversed unusually low latitudes in the eastern Pacific so that rather mild weather prevailed throughout the West. It was especially warm over the northern Rockies and Northern Plains as this southern Pacific air reached latitudes which normally experience considerably colder air masses in November both from the Canadian and northern Pacific source regions. Foehn warming on the leeward mountain slopes and anticyclonic circulation aloft undoubtedly enhanced the mildness of the air in much of this region.

The second half of November was warmer than normal over most sections of the United States (fig. 4B). The development of the trough over the central United States (fig. 1B) brought warm air to the entire eastern half of the country as southerly flow components set in ahead of the trough. Even though northwesterly flow developed over the western half of the United States, temperatures still remained generally above normal. This is attributable to the fast westerly flow crossing the west coast and the northern Rockies, which continued to bring mild Pacific air into the country and prevented major outbreaks of Canadian polar air masses from entering the circulation to the rear of the United States trough. Furthermore, the circulation pattern which existed over Canada throughout October [8], the first half of November (fig. 1A), and even the second half of November (fig. 1B) was one of fast zonal flow which prevented development of cold air over the Canadian source region. Mean temperatures in the layer 1000 to 700 mb. over central Canada (not shown) averaged as much as 5° to 6° C. above normal throughout October and November. Thus those outbreaks of Canadian air which did occur in the second half of November generally produced temperatures which were above normal in the northern border States and only slightly below normal even in the South Central States. Cool weather prevailed during this second half of November only in California, southern Nevada, and Arizona. Apparently the Pacific air masses had enough of a northerly origin to bring temperatures slightly below normal for these lower latitudes.

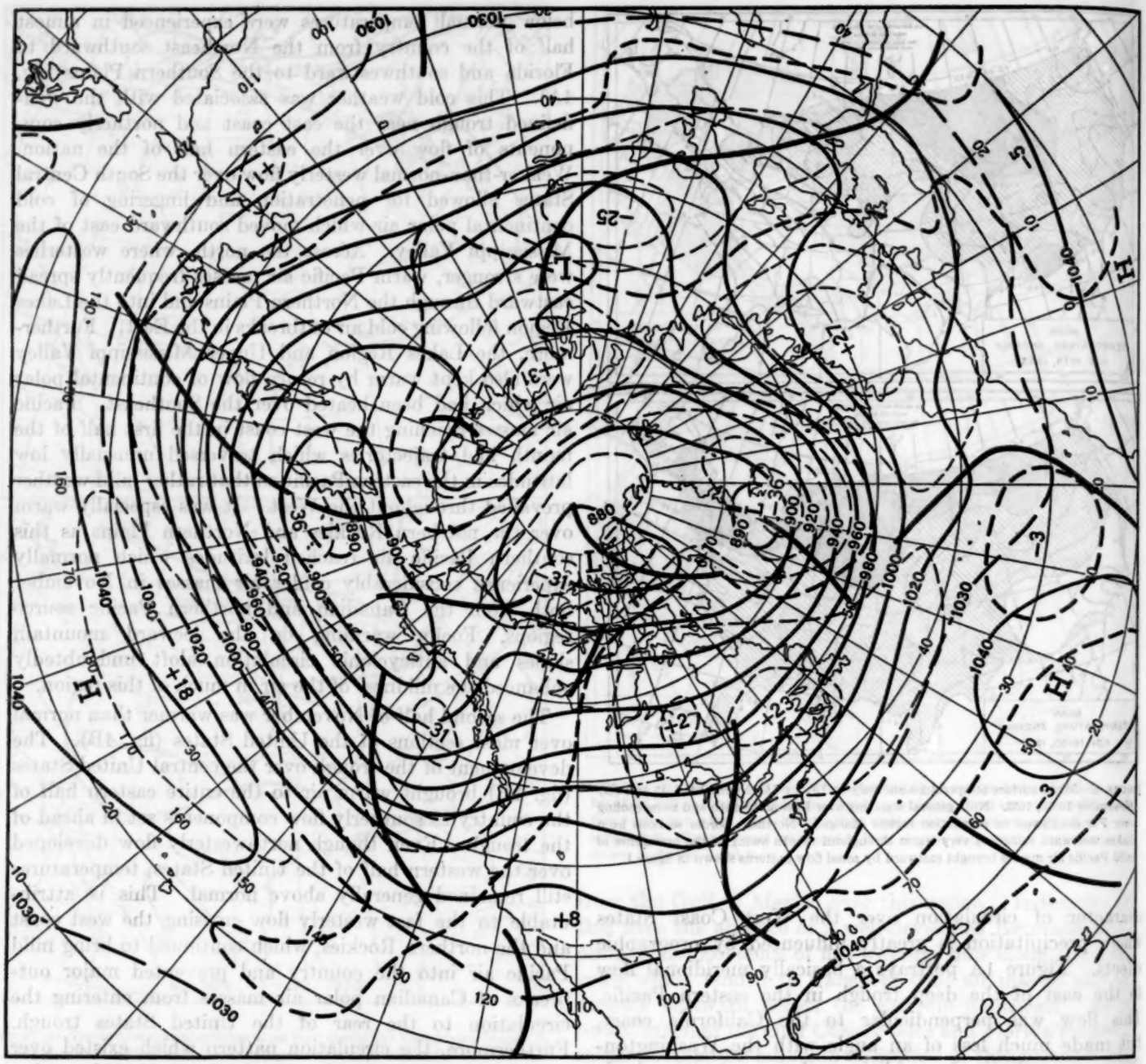

FIGURE 5.—Mean 700-mb. chart with height contours and departures from normal (both labeled in tens of feet) for October 31–November 29, 1953. This shows many of the individual features of figures 1A and 1B, so much so that four troughs exist between eastern Asia and the eastern Atlantic with rather short wave lengths for strong zonal flow.

MONTHLY MEAN CIRCULATION

In spite of the large contrasts in circulation regimes during November the monthly mean 700-mb. chart exhibits a fairly well-defined circulation pattern (fig. 5). As might be expected, it embodies characteristic features of both 15-day charts (fig. 1), so that a large wave number exists over the hemisphere with four major troughs from the east coast of Asia eastward to the eastern Atlantic. However, it was shown earlier in the discussion of figure 1 that the eastern Pacific trough existed only in the first half of the month while the eastern Atlantic trough at middle and low latitudes only developed in the second half of the month. Thus in such transition states as these the monthly mean chart may exhibit some abnormally short wave lengths.

One of the more interesting features of figure 5 is the large area of above normal heights which prevailed over much of Canada, the United States, and the western Atlantic. This represented a good deal of persistence from October [7] and these departures only began to fall away over central North America during the second half of

November. Associated with this extensive positive anomaly, with centers over Hudson Bay and the Gulf of St. Lawrence, were a large area of positive mean sea level pressure anomaly over eastern Canada (Chart XI inset) and an abnormally high frequency of sea level anticyclones traversing central and eastern Canada (Chart IX).

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THE STRONG JET OVER THE SOUTHWESTERN PLAINS STATES, NOVEMBER 24–25, 1953

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INTRODUCTION

During the period November 22–27, 1953 the 300-mb. jet entering the west coast of North America strengthened and moved east-southeastward to the Gulf of Mexico, then northeastward up the east coast. From 0300 GMT November 24 to 1500 GMT November 25 inclusive some high speed, upper level winds were reported including the following:

Between 150 and 200 knots	*Over 200 knots*
Denver, Colo.	Lander, Wyo.
Amarillo, Tex.	Oklahoma City, Okla.
St. Cloud, Minn.	
Oklahoma City, Okla.	

As such wind speeds are not often observed it was felt that an investigation of the flow in the region surrounding this strong jet stream might throw some light on the processes occurring during times of maximum winds.

This present paper deals with the methods used in constructing various charts from which a study was made of the relationship of the position of the jet to special features at other levels, the movement of areas of wind speed maxima, and the calculated maximum speeds.

As the time allotted for this study was limited, a small area, covering only the southwestern Plains States, was chosen in order to assure an accurate analysis on all charts. The charts discussed are for 1500 and 2100 GMT on the 24th and 0300 and 1500 GMT on the 25th.

CONSTRUCTION OF CHARTS

The first step in this study was the precise analysis of the 300-mb. charts to be used. The 300-mb. level was chosen because it is high enough to be near the level of maximum winds and low enough to supply an appreciable number of reports. As an aid in obtaining an accurate 300-mb. analysis, one that would be consistent with lower level analysis, the 700-mb. chart, on which the data coverage is usually adequate, was chosen as a base for a thickness buildup to 300-mb.

After the 700-mb. charts were analyzed, the 700 to 300-mb. thermal winds were computed and plotted along with the 700 to 300-mb. height difference values. In analyzing the 700 to 300-mb. height difference charts, it was noted that in some cases the thermal winds were inconsistent with the gradient of height differences. In such cases, the height differences were assumed to be more nearly correct. The 300-mb. charts were then constructed by graphical addition of the 700-mb. charts and 700 to 300-mb. height difference charts. The intermediate 300-mb. chart for 2100 GMT, because of the sparsity of data, was constructed in the following manner. Mean charts were analyzed for the 700-mb. level and 700 to 300-mb. height difference from the data for 1500 GMT on the 24th and 0300 GMT on the 25th. From these mean charts a 300-mb. chart was constructed and then adjusted to fit available 2100 GMT data.

The 300-mb. contours were given a minimum of smoothing since smoothing of the analysis eradicates the very features that one desires to find, i. e., variations in the strength of the winds [1].

The next task was to locate the jet axes on the 300-mb. charts. In locating these jet axes, the following empirical rules were used: (1) The 300-mb. jet axis in nearly all cases is located above or slightly to the left of the 500-mb. jet axis when the jet extends down to the 500-mb. level [1]. (2) A jet axis with strong winds below the 200-mb. level is usually situated parallel to the 200-mb. isotherms and below the zone of isotherm concentration, with cold air to the right and warm air to the left of the axis looking downstream [1]. (3) The axis of the jet is usually coincident with the zone of maximum packing of contours located by use of geostrophic wind measurements. (4) The maximum isotach gradient is usually to the left of the jet axis looking downstream.

FEATURES OF THE JET

The position of the jet axis on the 1500 GMT chart of the 24th (fig. 1) was over central Wyoming and Colorado, southern Oklahoma and Arkansas. A velocity maximum extended into Wyoming, while another was centered near the Texas Panhandle. An irregularity in the isotach pattern can be noticed over central Texas where a jet finger had already appeared. If we look at the correspondence between the concentration of the 200-mb. isotherms and the position of the 300-mb. jet (fig. 2), we

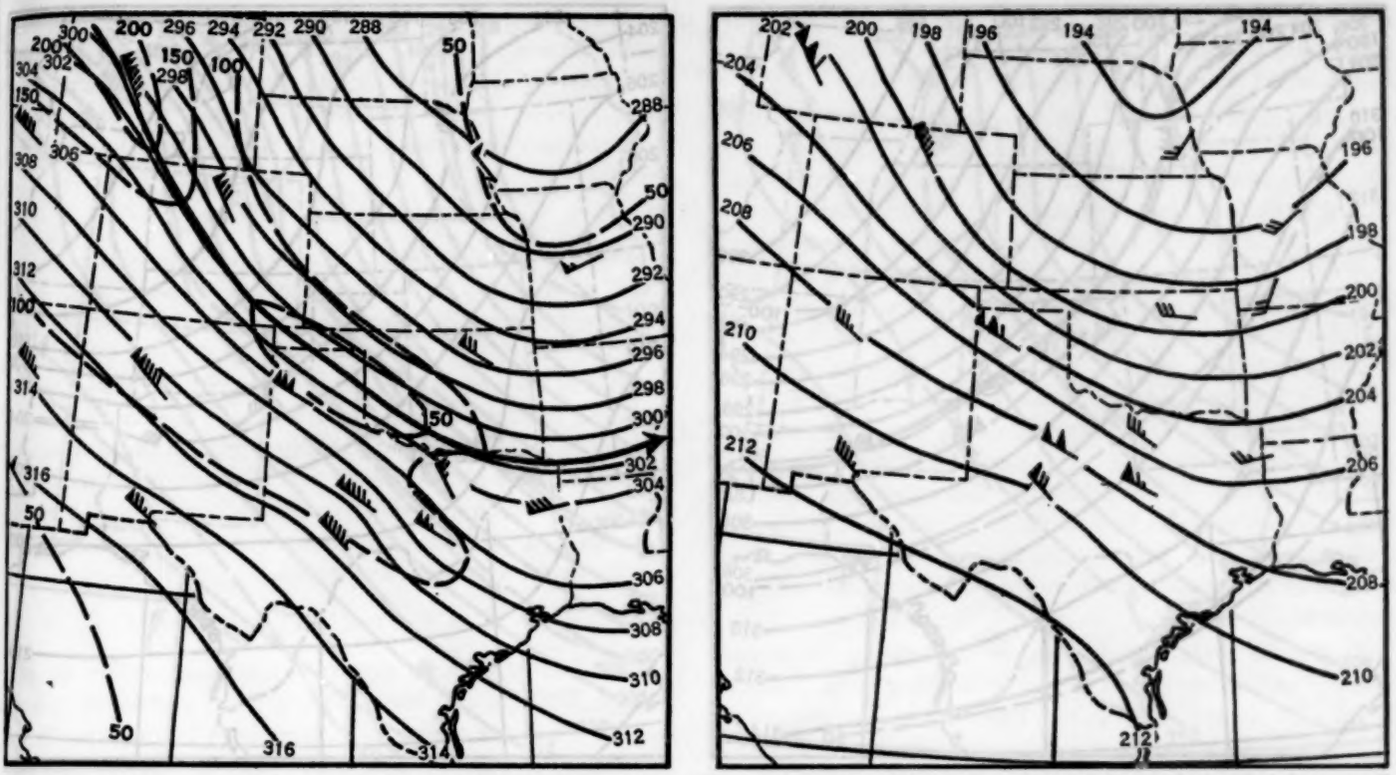

FIGURE 1.—Left: 300-mb. chart for 1500 GMT, November 24, 1953 showing contours (solid lines) and isotachs labeled in knots (dashed lines). Jet is heavy arrowed line. Right: 700-300-mb. height difference chart for 1500 GMT, November 24, 1953.

FIGURE 2.—200-mb. isotherms analyzed for 2° C. intervals superimposed on 300-mb. jet for 1500 GMT, November 24, 1953.

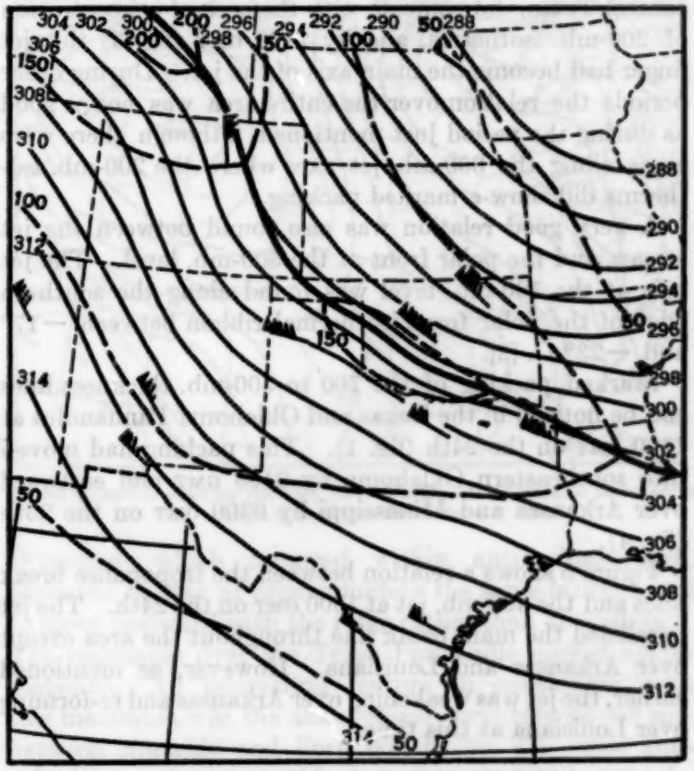

FIGURE 3.—300-mb. chart for 2100 GMT, November 24, 1953 showing contours and isotachs labeled in knots. Jet is heavy arrowed line.

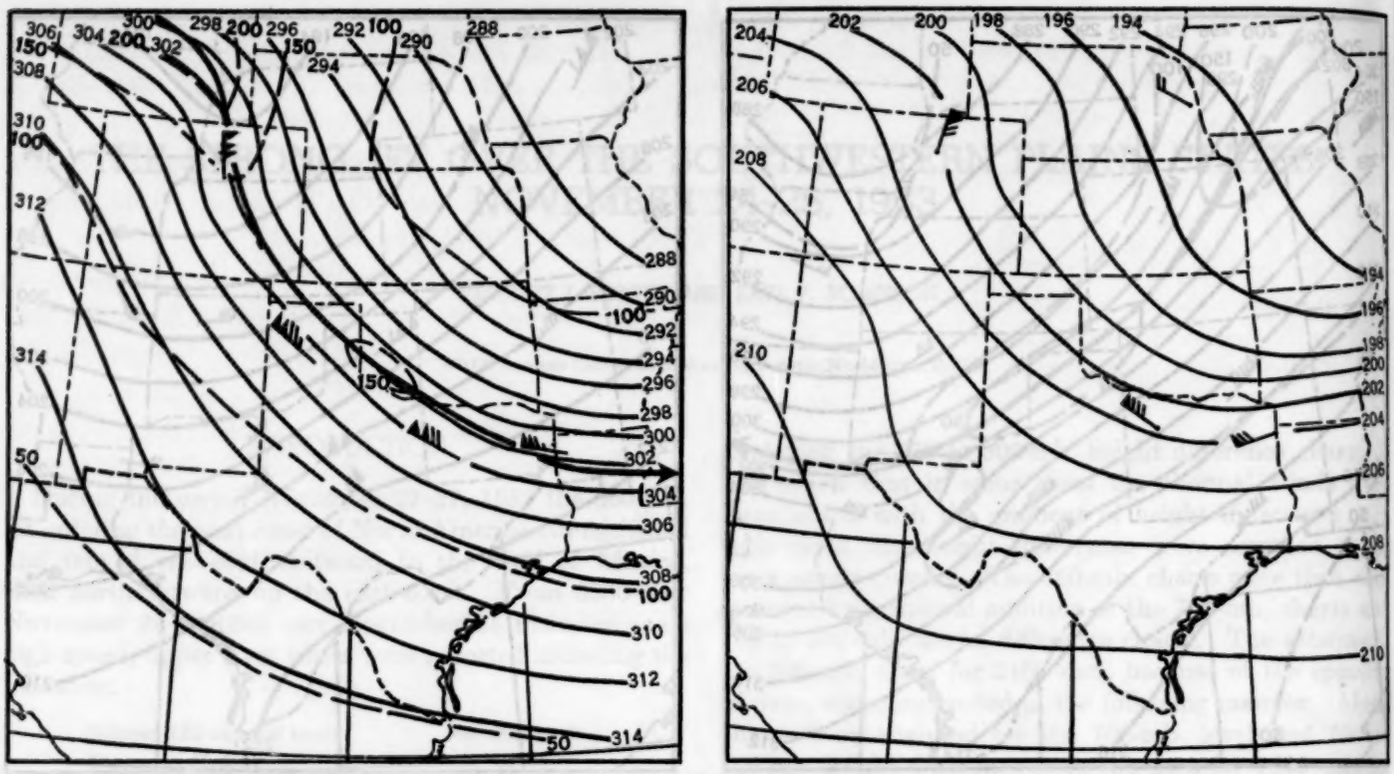

FIGURE 4.—Left: 300-mb. chart for 0300 GMT, November 25, 1953 showing contours (solid lines) and isotachs labeled in knots (dashed lines). Jet is heavy arrowed line. Right: 700-300-mb. height difference chart for 0300 GMT, November 25, 1953.

find an inconsistency in the Arkansas-Louisiana area where the 300-mb. jet did not coincide with the packing of the 200-mb. isotherms. However, it may be seen from the isotachs (fig. 1) that the jet finger, already started in central Texas, did coincide with the area of concentration of 200-mb. isotherms, and by 2100 GMT (fig. 3) this jet finger had become the main axis of the jet. During other periods the relation over the entire area was not as good as during the period just mentioned, although there were areas along the 300-mb. jet axes where the 200-mb. isotherms did show a marked packing.

A very good relation was also found between the jet stream and the polar front at the 500-mb. level. The jet axis at the 500-mb. level was found along the southern edge of the polar front isothermal ribbon between −17° and −23° C. [2].

Marked packing of the 700 to 300-mb. thickness lines can be noticed in the Texas and Oklahoma Panhandles at 1500 GMT on the 24th (fig. 1). This packing had moved into southeastern Oklahoma by 2100 GMT and eastward over Arkansas and Mississippi by 0300 GMT on the 25th (fig. 4).

Figure 5 shows a relation between the tropopause break lines and the 300-mb. jet at 1500 GMT on the 24th. The jet paralleled the main break line throughout the area except over Arkansas and Louisiana. However, as mentioned earlier, the jet was weakening over Arkansas and re-forming over Louisiana at this time.

FIGURE 5.—Tropopause breaks (stippled line) superimposed on 300-mb. jet (solid arrow) for 1500 GMT, November 24, 1953. Tropopause height lines are labeled in thousands of feet.

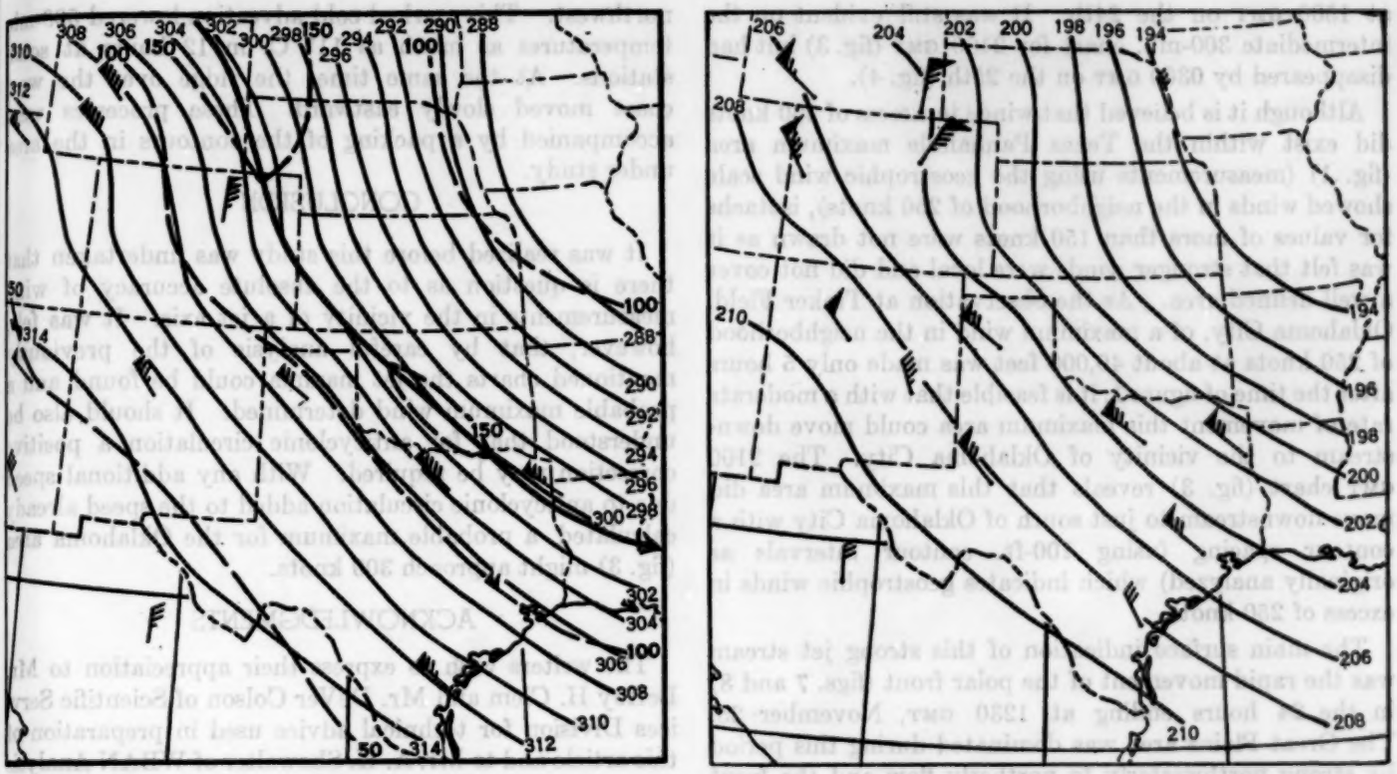

FIGURE 6.—Left: 300-mb. chart for 1500 GMT, November 25, 1953, showing contours (solid lines) and isotachs labeled in knots (dashed lines). Jet is heavy arrowed line. Right: 700-300-mb. height difference chart for 1500 GMT, November 25, 1953.

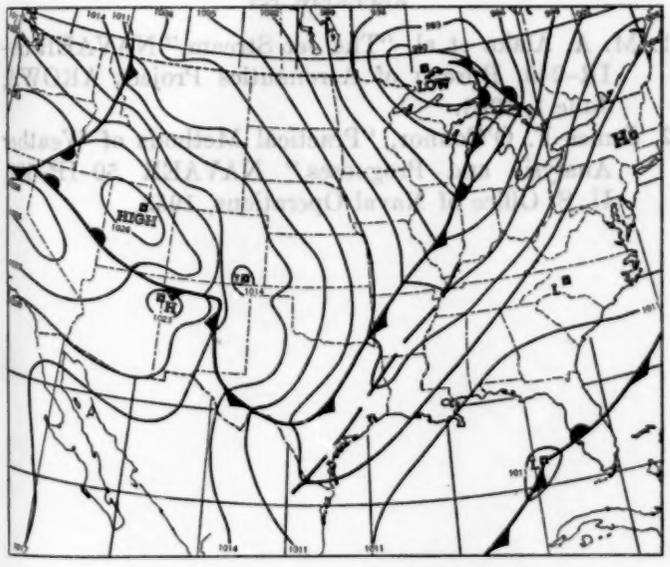

FIGURE 7.—Surface chart for 1230 GMT, November 24, 1953.

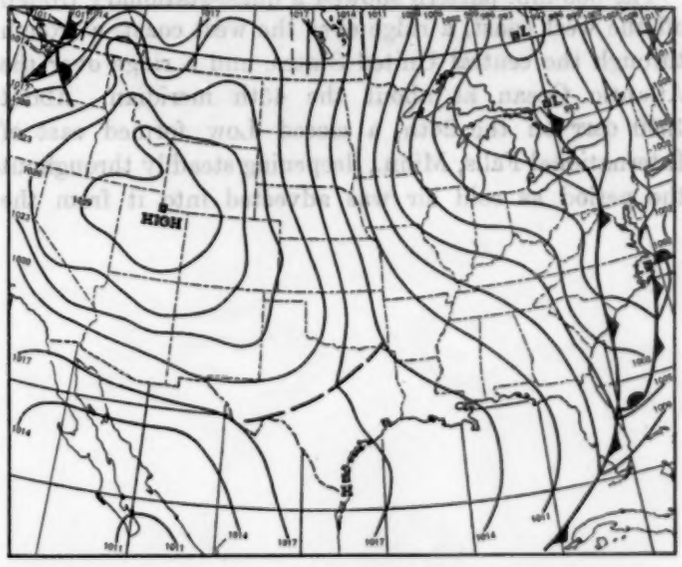

FIGURE 8.—Surface chart for 1230 GMT, November 25, 1953. Note rapid movement of front in 24 hours from time of figure 7.

The changes in the position of the jet axis at 300 mb. over the period of time under study were only slight (figs. 1, 3, 4, and 6). The least change occurred over southeastern Oklahoma where the jet axis remained nearly stationary and pivoted to acquire a more north-south tilt.

The two jet maxima at 1500 GMT on the 24th (fig. 1), one in Wyoming and the other over the Texas Panhandle, moved very little during the period. The maximum over Wyoming, which occurred within anticyclonic flow, appeared to stay at approximately the same latitude and to move eastward with the ridge rather than downstream. The maximum over the Texas Panhandle moved southeastward. An interesting feature in connection with this maximum was the anticyclonic curvature at 300 mb. between Amarillo and Fort Worth (fig. 1). This anticylonic curvature was evident at all levels, 700 to 150 mb.,

at 1500 GMT on the 24th. It was still evident on the intermediate 300-mb. chart for 2100 GMT (fig. 3) but had disappeared by 0300 GMT on the 25th (fig. 4).

Although it is believed that winds in excess of 200 knots did exist within the Texas Panhandle maximum area (fig. 1) (measurements using the geostrophic wind scale showed winds in the neighborhood of 250 knots), isotachs for values of more than 150 knots were not drawn as it was felt that stronger winds were local and did not cover a well defined area. As the observation at Tinker Field, Oklahoma City, of a maximum wind in the neighborhood of 250 knots at about 40,000 feet was made only 5 hours after the time of figure 1, it is feasible that with a moderate rate of movement this maximum area could move downstream to the vicinity of Oklahoma City. The 2100 GMT chart (fig. 3) reveals that this maximum area did move downstream to just south of Oklahoma City with a contour spacing (using 100-ft. contour intervals as originally analyzed) which indicates geostrophic winds in excess of 250 knots.

The main surface indication of this strong jet stream was the rapid movement of the polar front (figs. 7 and 8) in the 24 hours ending at 1230 GMT, November 25. The Great Plains area was dominated during this period by strong northwesterly to northerly flow and the front was pushed rapidly southward and eastward at an average rate of 36 knots for the 24-hour period.

The 500-mb. pattern showed a quasi-stationary trough off the west coast, a ridge over the west coast, a trough through the central United States, and a ridge over the Atlantic Ocean at about the 45th meridian. About 1500 GMT on the 24th, a closed Low formed east of International Falls, Minn., deepening steadily throughout the period as cold air was advected into it from the northwest. This marked cold advection lowered 500-mb. temperatures as much as 11° C. in 12 hours at some stations. At the same time, the ridge over the west coast moved slowly eastward. These processes were accompanied by a packing of the contours in the area under study.

CONCLUSION

It was realized before this study was undertaken that there is question as to the absolute accuracy of wind measurements in the vicinity of a jet axis. It was felt, however, that by careful analysis of the previously mentioned charts the jet maxima could be found and a probable maximum wind determined. It should also be understood that for anticyclonic circulation a positive correction may be required. With any additional speed due to anticyclonic circulation added to the speed already calculated, a probable maximum for the Oklahoma area (fig. 3) might approach 300 knots.

ACKNOWLEDGMENTS

The writers wish to express their appreciation to Mr. LeRoy H. Clem and Mr. DeVer Colson of Scientific Services Division for technical advice used in preparation of this article and to Mr. A. K. Showalter of WBAN Analysis Center for suggestions on the construction of the various charts used in the article.

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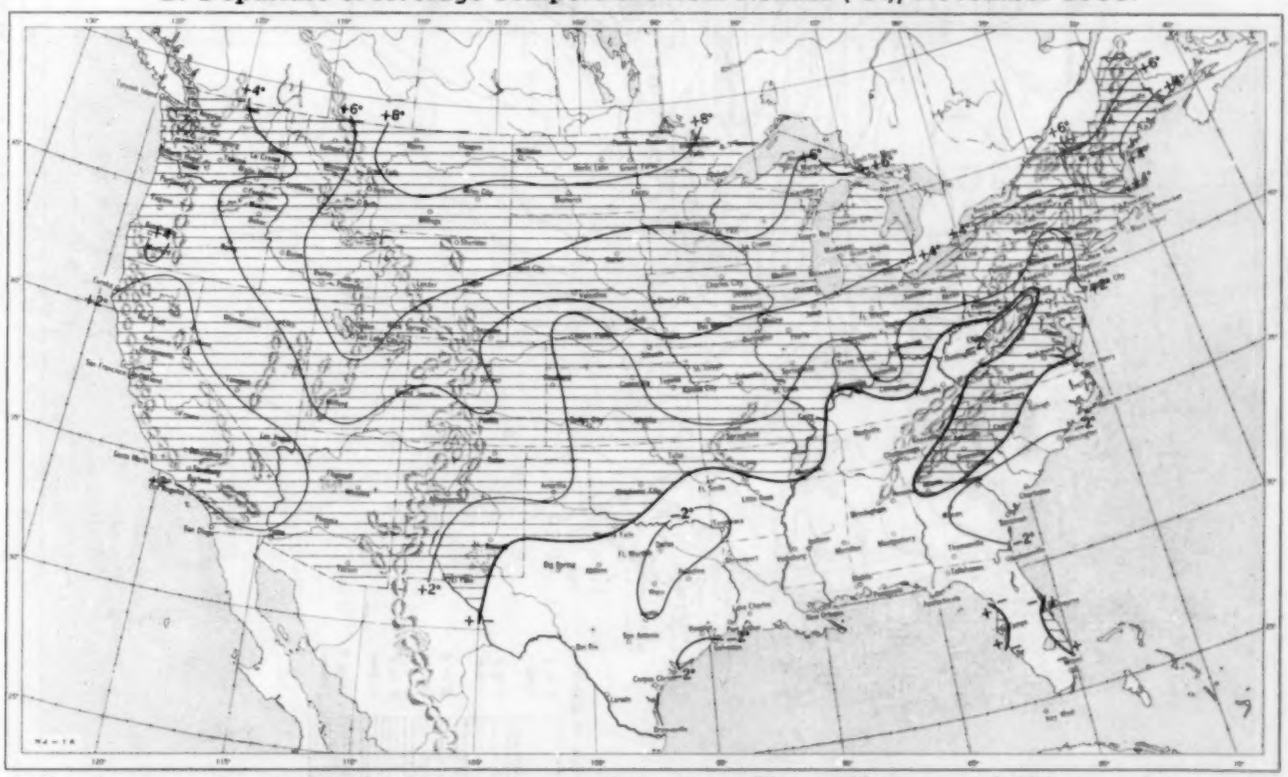
U. S. GOVERNMENT PRINTING OFFICE: 1954

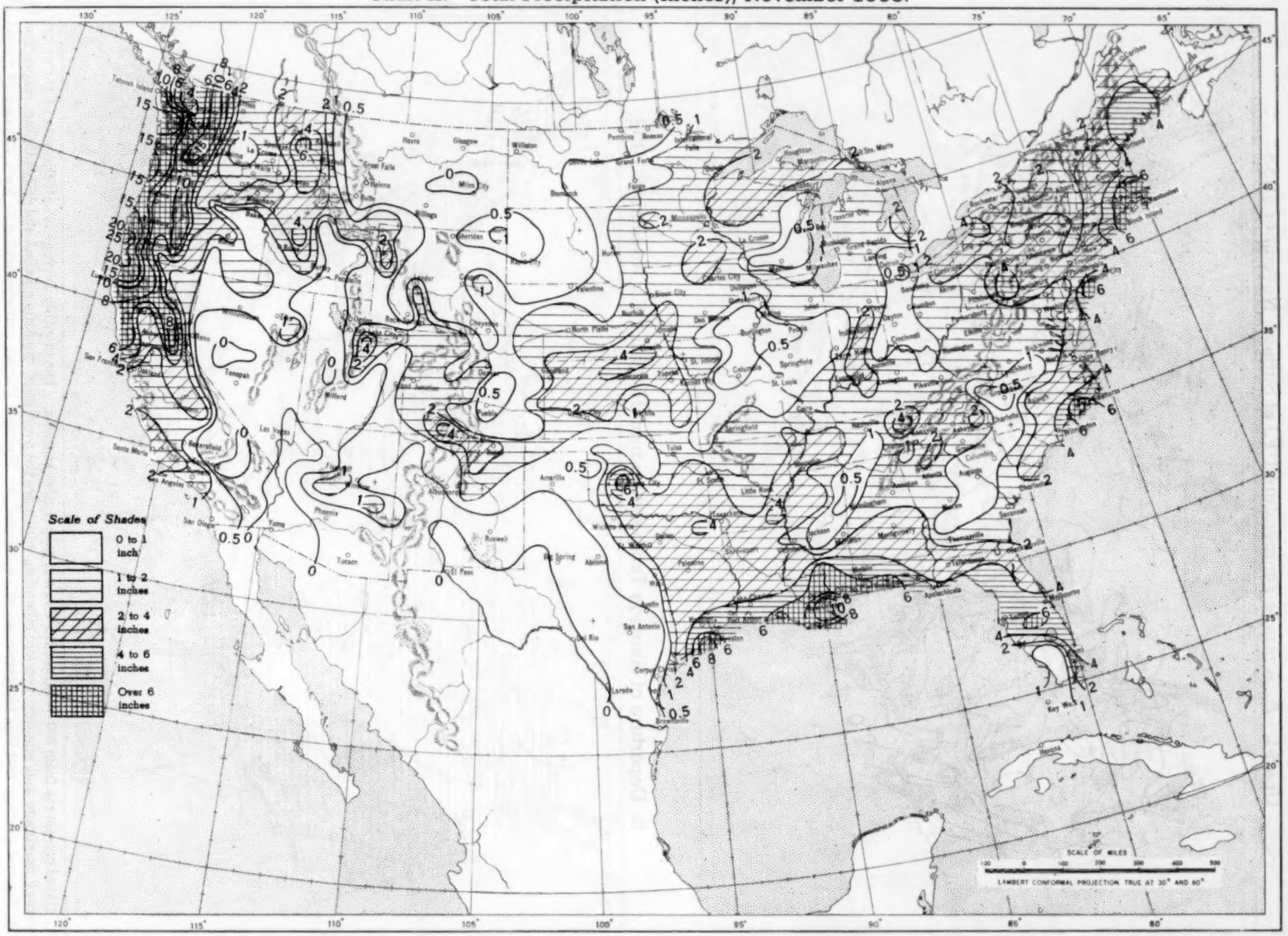
Chart I. A. Average Temperature (°F.) at Surface, November 1953.

B. Departure of Average Temperature from Normal (°F.), November 1953.



A. Based on reports from 800 Weather Bureau and cooperative stations. The monthly average is half the sum of the monthly average maximum and monthly average minimum, which are the average of the daily maxima and daily minima, respectively.
B. Normal average monthly temperatures are computed for Weather Bureau stations having at least 10 years of record.

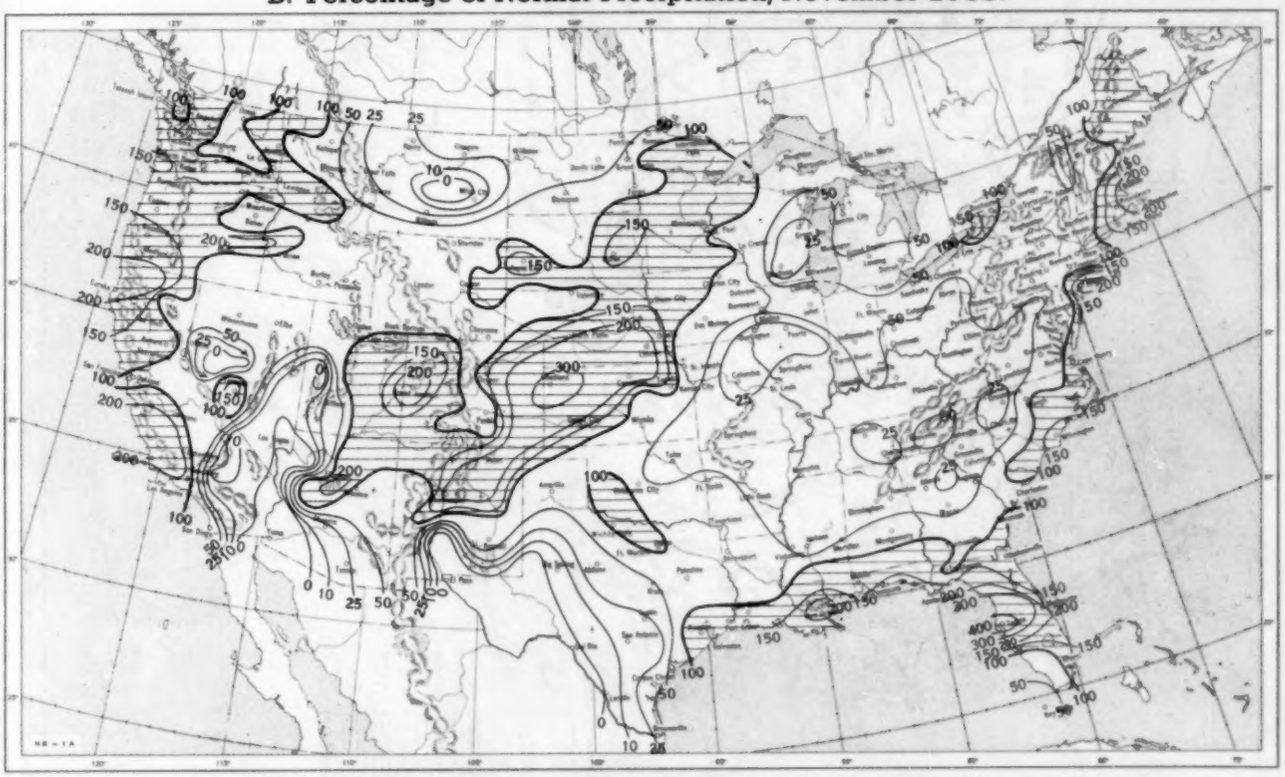
Chart II. Total Precipitation (Inches), November 1953.


Scale of Shades
0 to 1 inch
1 to 2 inches
2 to 4 inches
4 to 6 inches
Over 6 inches
SCALE OF MILES
LAMBERT CONFORMAL PROJECTION, TRUE AT 30° AND 60°

Based on daily precipitation records at 800 Weather Bureau and cooperative stations.

Chart III. A. Departure of Precipitation from Normal (Inches), November 1953.

B. Percentage of Normal Precipitation, November 1953.

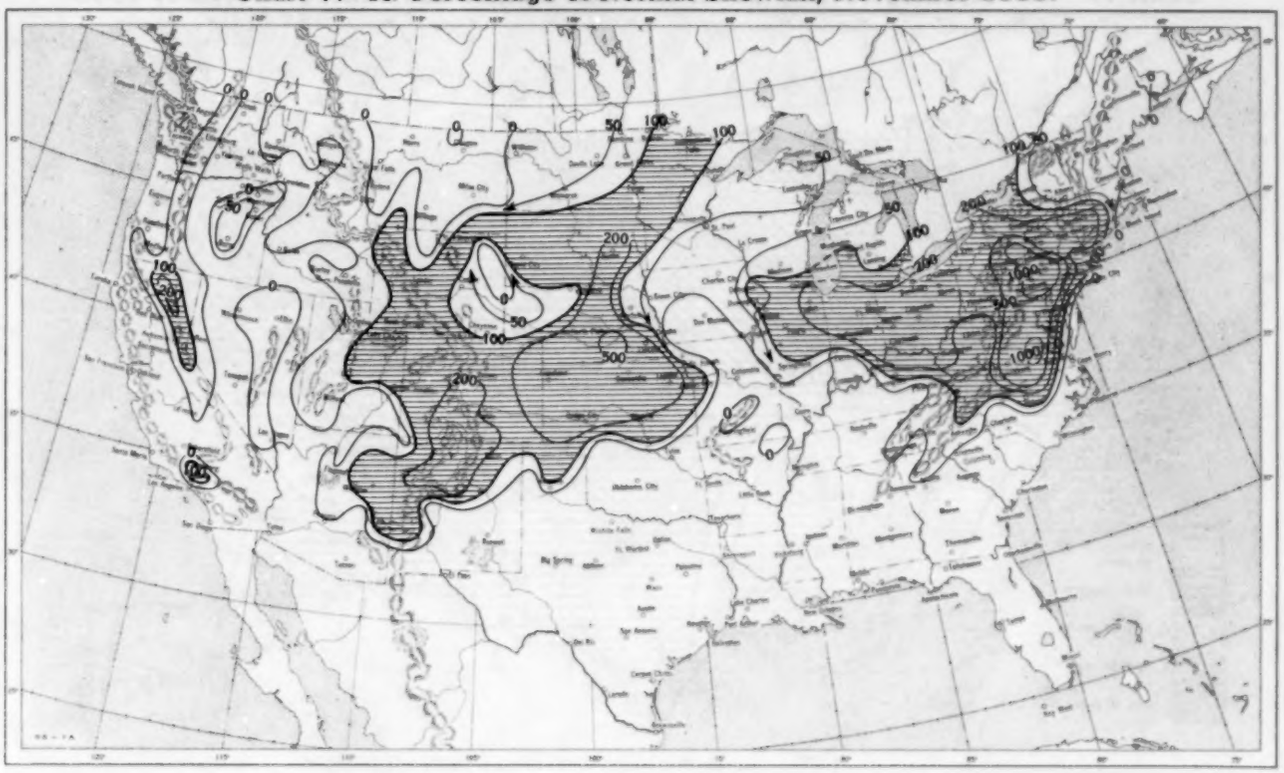


Normal monthly precipitation amounts are computed for stations having at least 10 years of record.

Chart IV. Total Snowfall (Inches), November 1953.

This is the total of unmelted snowfall recorded during the month at Weather Bureau and cooperative stations. This chart and Chart V are published only for the months of November through April although of course there is some snow at higher elevations, particularly in the far West, earlier and later in the year.

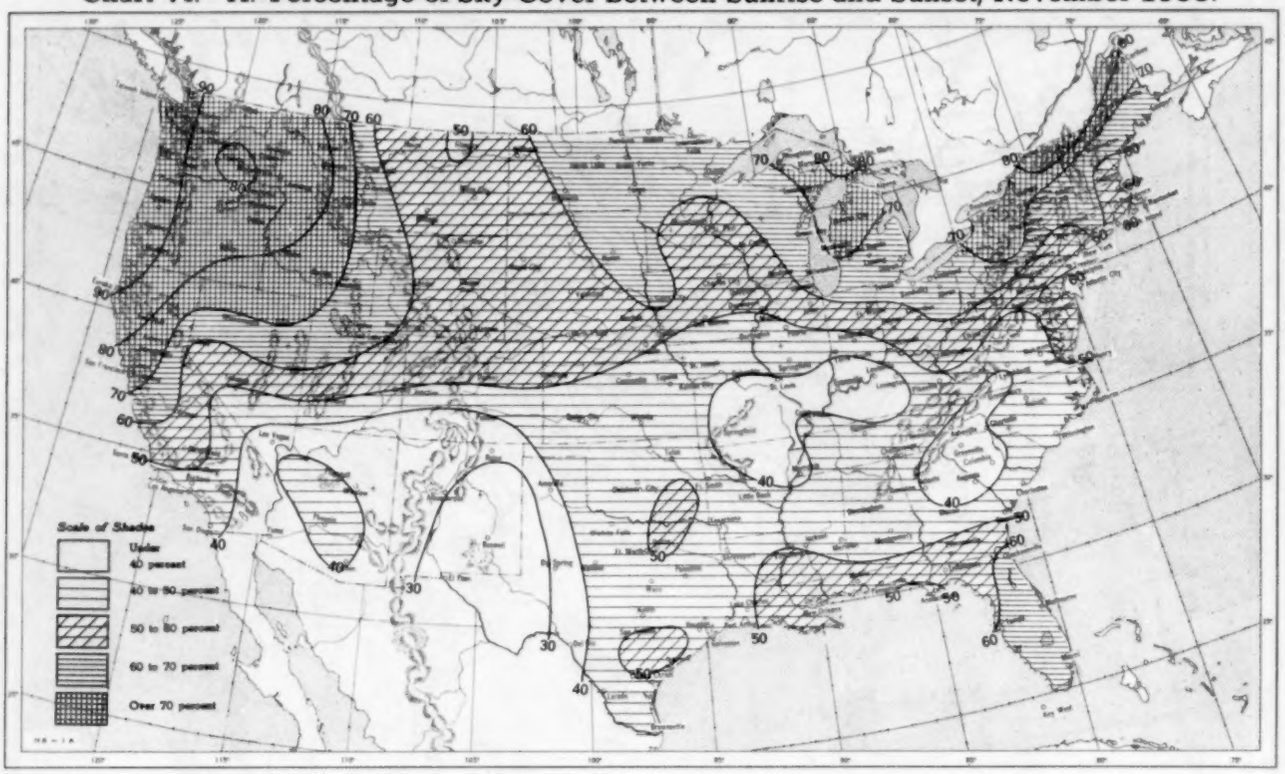
Chart V. A. Percentage of Normal Snowfall, November 1953.



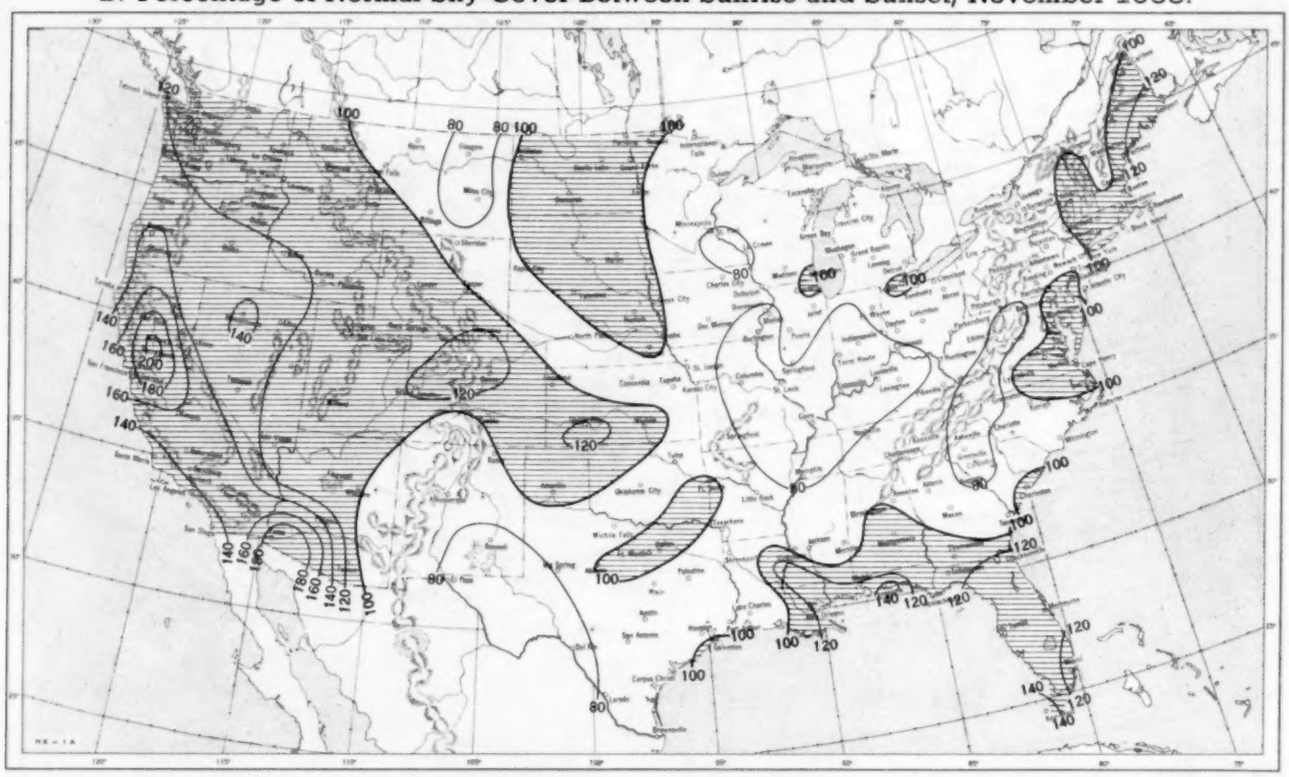
B. Depth of Snow on Ground (Inches)

A. Amount of normal monthly snowfall is computed for Weather Bureau stations having at least 10 years of record.
B. Shows depth currently on ground at 7:30 a. m. E.S.T., of the Tuesday nearest the end of the month. It is based on reports from Weather Bureau and cooperative stations. Dashed line shows greatest southern extent of snowcover during month.

Chart VI. A. Percentage of Sky Cover Between Sunrise and Sunset, November 1953.



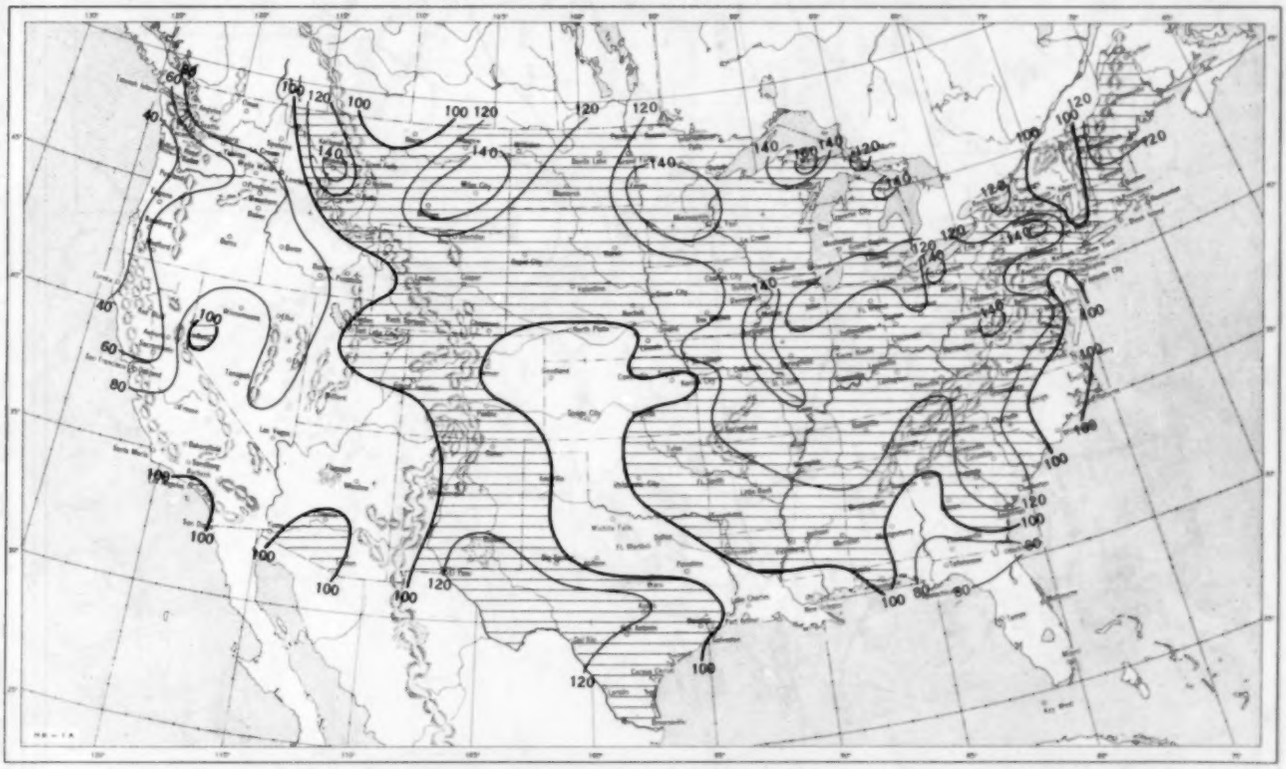
B. Percentage of Normal Sky Cover Between Sunrise and Sunset, November 1953.



A. In addition to cloudiness, sky cover includes obscuration of the sky by fog, smoke, snow, etc. Chart based on visual observations made hourly at Weather Bureau stations and averaged over the month. B. Computations of normal amount of sky cover are made for stations having at least 10 years of record.

Chart VII. A. Percentage of Possible Sunshine, November 1953.

B. Percentage of Normal Sunshine, November 1953.



A. Computed from total number of hours of observed sunshine in relation to total number of possible hours of sunshine during month. B. Normals are computed for stations having at least 10 years of record.

Chart VIII. Average Daily Values of Solar Radiation, Direct + Diffuse, November 1953. Inset: Percentage of Normal Average Daily Solar Radiation, November 1953.

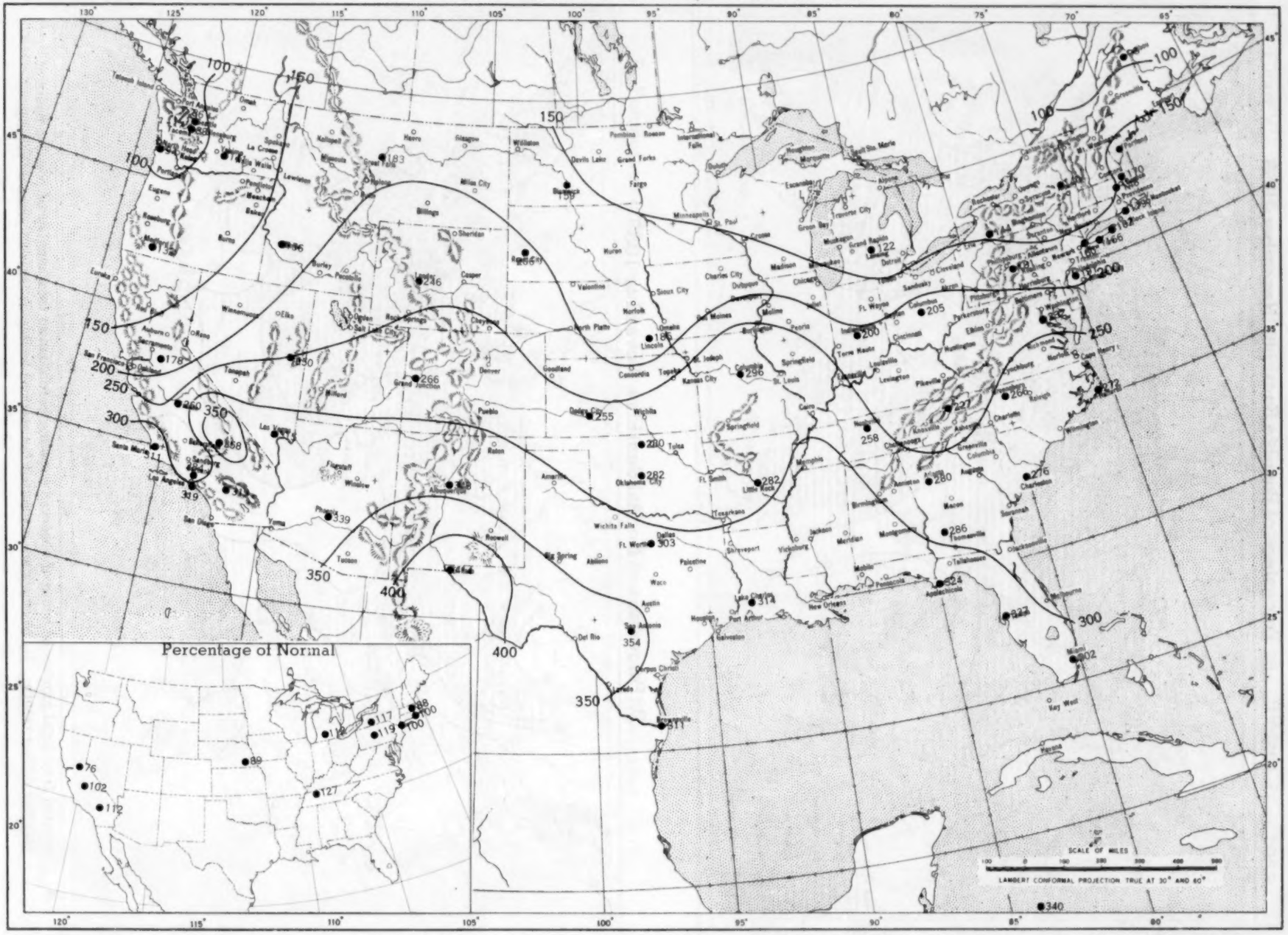
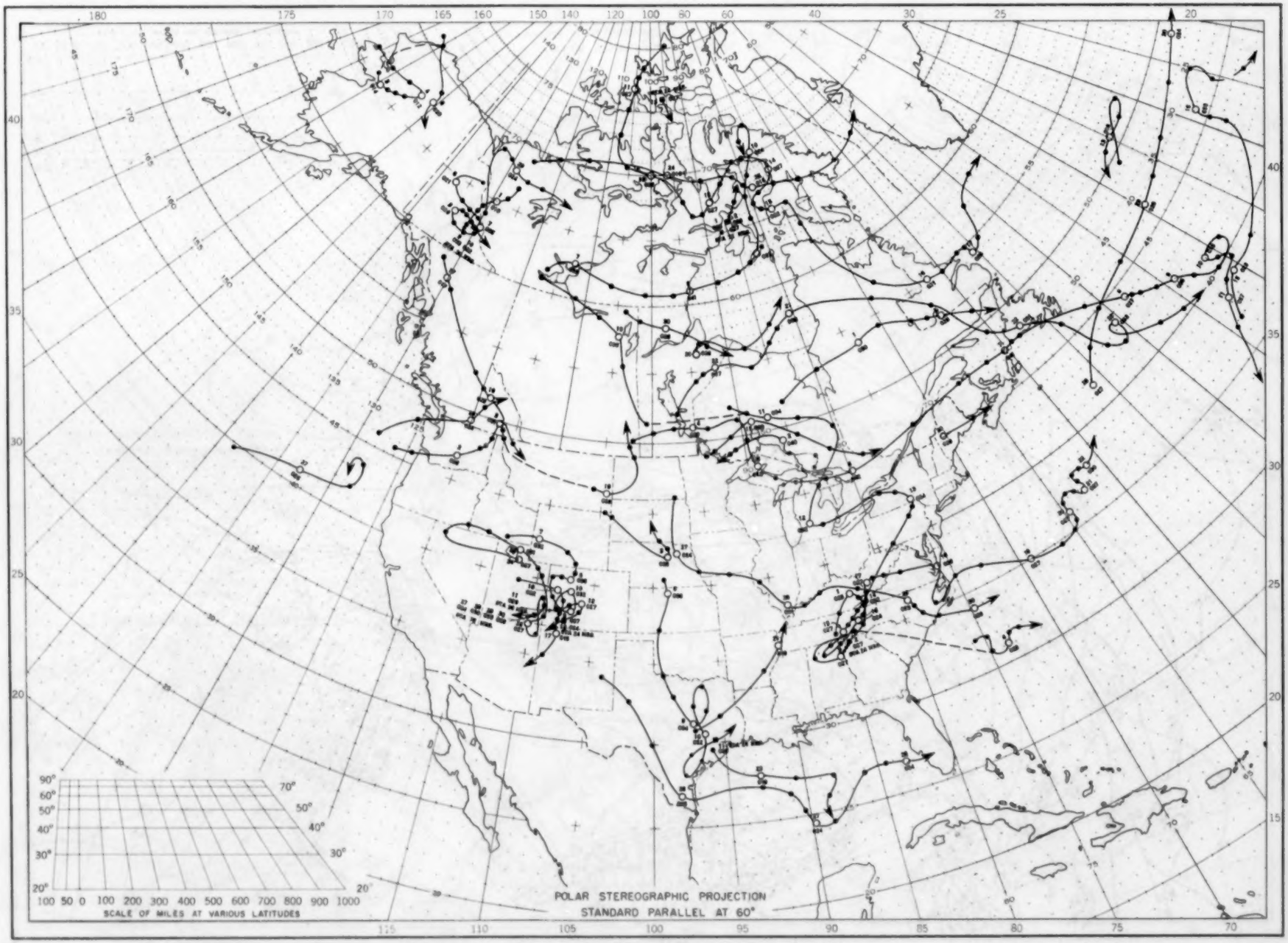


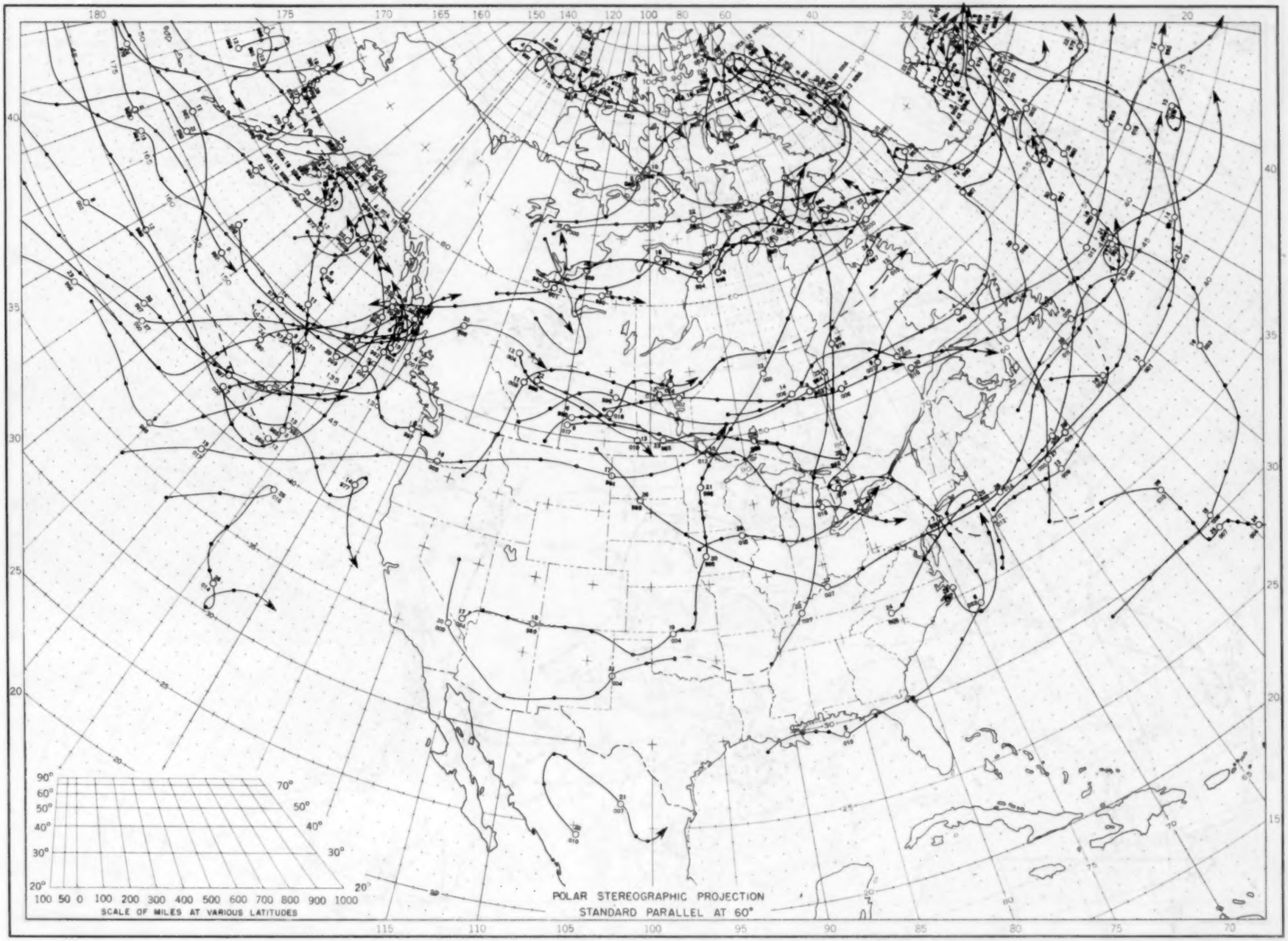
Chart shows mean daily solar radiation, direct + diffuse, received on a horizontal surface in langleys (1 langley = 1 gm. cal. cm. $^{-2}$). Basic data for isolines are shown on chart. Further estimates are obtained from supplementary data for which limits of accuracy are wider than for those data shown. Normals are computed for stations having at least 9 years of record.

Chart IX. Tracks of Centers of Anticyclones at Sea Level, November 1953.


SCALE OF MILES AT VARIOUS LATITUDES
100 50 0 100 200 300 400 500 600 700 800 900 1000
POLAR STEREOGRAPHIC PROJECTION
STANDARD PARALLEL AT 60°

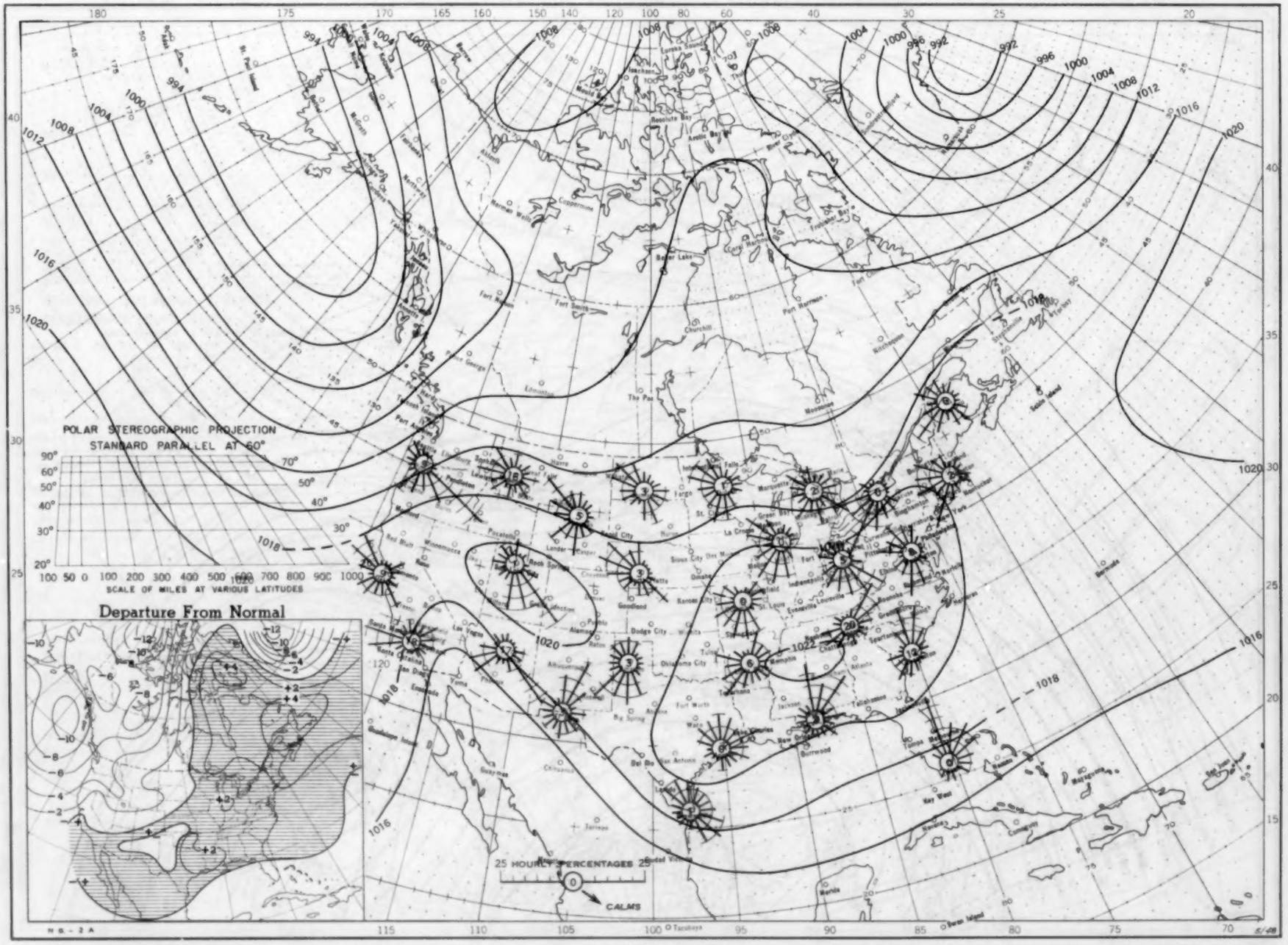
Circle indicates position of center at 7:30 a. m. E. S. T. Figure above circle indicates date, figure below, pressure to nearest millibar. Dots indicate intervening 6-hourly positions. Squares indicate position of stationary center for period shown. Dashed line in track indicates reformation at new position. Only those centers which could be identified for 24 hours or more are included.

Chart X. Tracks of Centers of Cyclones at Sea Level, November 1953.


POLAR STEREOGRAPHIC PROJECTION
STANDARD PARALLEL AT 60°
SCALE OF MILES AT VARIOUS LATITUDES
100 50 0 100 200 300 400 500 600 700 800 900 1000

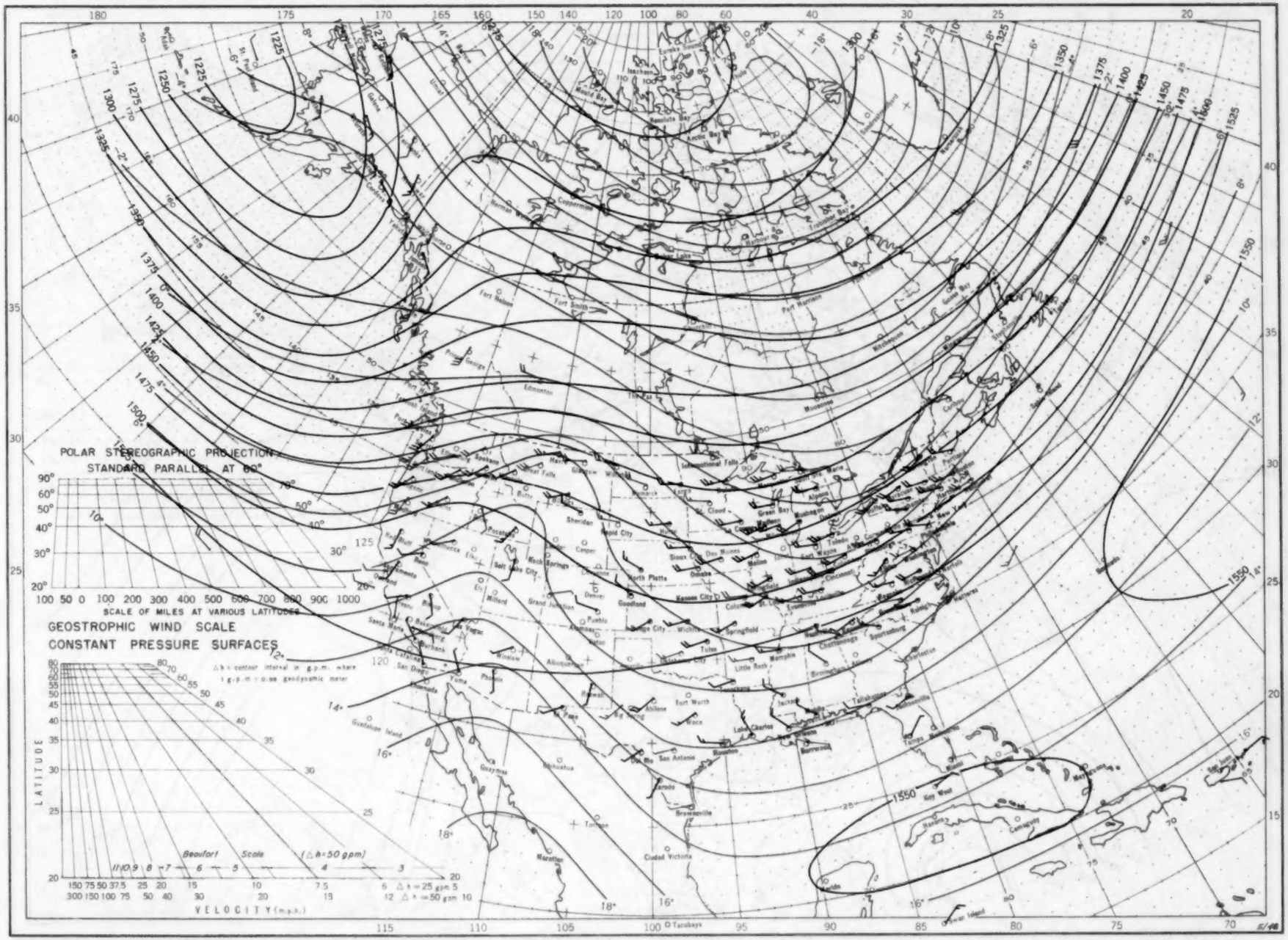
Circle indicates position of center at 7:30 a. m. E. S. T. See Chart IX for explanation of symbols.

Chart XI. Average Sea Level Pressure (mb.) and Surface Windroses, November 1953. Inset: Departure of Average Pressure (mb.) from Normal, November 1953.



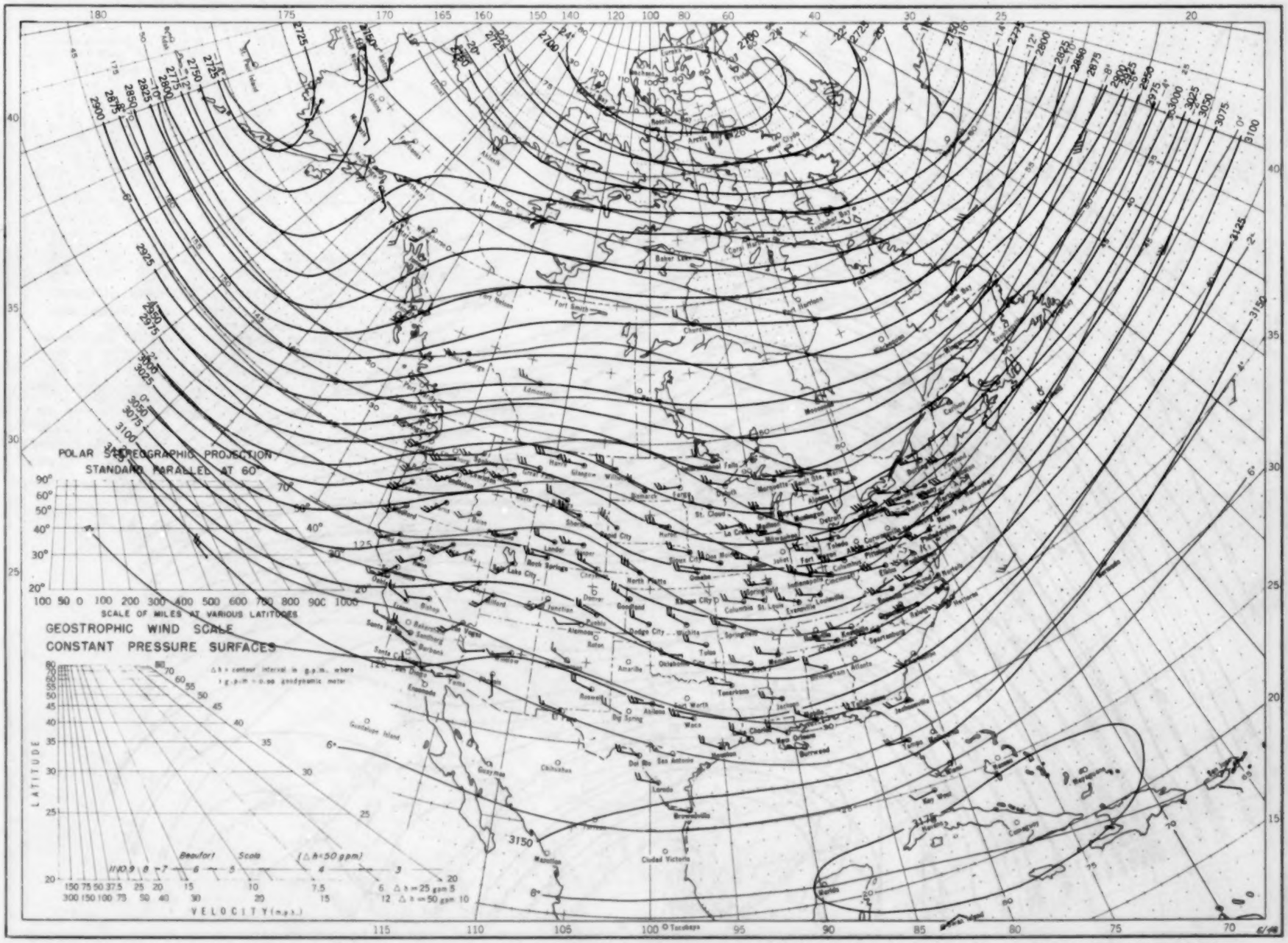
Average sea level pressures are obtained from the averages of the 7:30 a.m. and 7:30 p.m. E.S.T. readings. Windroses show percentage of time wind blew from 16 compass points or was calm during the month. Pressure normals are computed for stations having at least 10 years of record and for 10° intersections in a diamond grid based on readings from the Historical Weather Maps (1899-1939) for the 20 years of most complete data coverage prior to 1940.

Chart XII. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 850-mb. Pressure Surface, Average Temperature in °C. at 850 mb., and Resultant Winds at 1500 Meters (m.s.l.), November 1953.



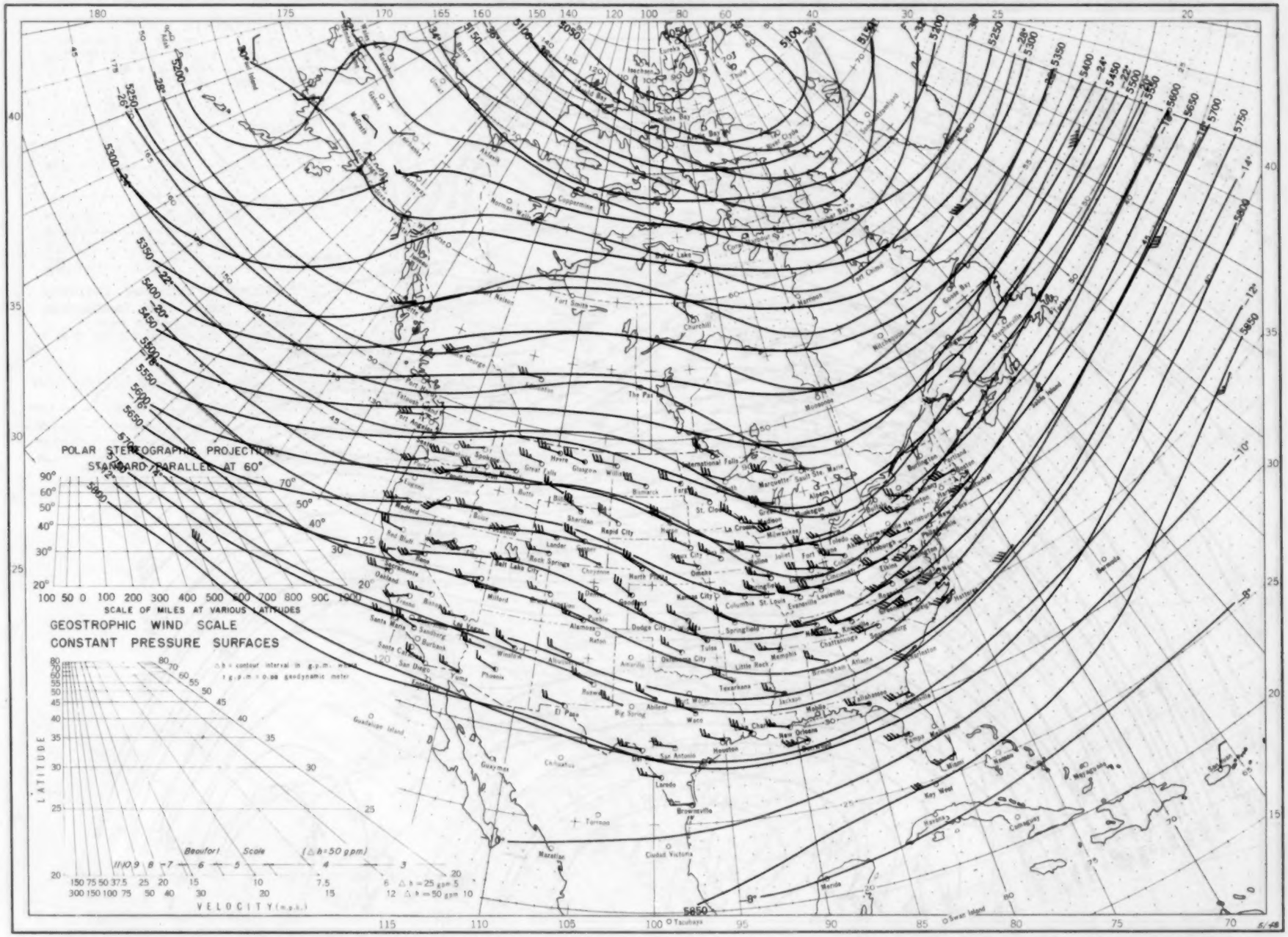
Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins taken at 0300 G. M. T.

Chart XIII. Average Dynamic Height in Geopotential Meters (1 g.p.m.. = 0.98 dynamic meters) of the 700-mb. Pressure Surface, Average Temperature in °C. at 700 mb., and Resultant Winds at 3000 Meters (m.s.l.), November 1953.



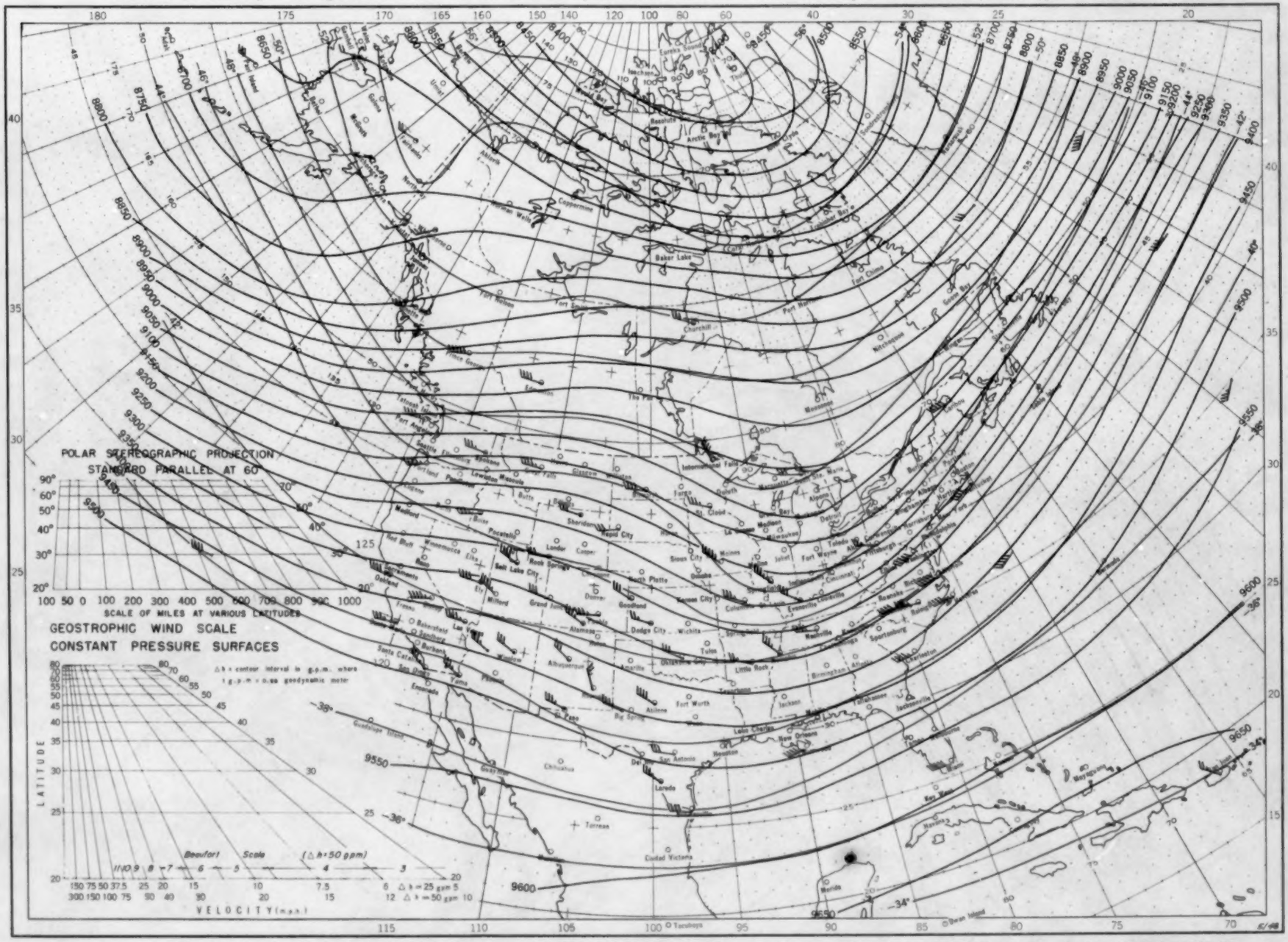
Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins taken at 0300 G. M. T.

Chart XIV. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 500-mb. Pressure Surface, Average Temperature in °C. at 500 mb., and Resultant Winds at 5000 Meters (m.s.l.), November 1953.



Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins at 0300 G. M. T.

Chart XV. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 300-mb. Pressure Surface, Average Temperature in °C. at 300 mb., and Resultant Winds at 10,000 Meters (m.s.l.), November 1953.


POLAR STEREOGRAPHIC PROJECTION
STANDARD PARALLEL AT 60°
SCALE OF MILES AT VARIOUS LATITUDES
GEOSTROPHIC WIND SCALE
CONSTANT PRESSURE SURFACES
LATITUDE
VELOCITY (m.p.h.)
Beaufort Scale
Δh = contour interval in g.p.m. where 1 g.p.m. = 0.98 geodynamic meter

Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins at 0300 G. M. T.